A smart multi-hop hierarchical routing protocol for efficient video communication over wireless multimedia sensor networks

Denis do Rosário*, Rodrigo Costa*, Helder Paraense*, Kássio Machado*,
Eduardo Cerqueira* and Torsten Braun†
* Federal University of Para (UFPA), Belem – PA – Brazil
† Institute of Computer Science and Applied Mathematics, University of Bern, Bern – Switzerland
Email denis@ufpa.br, rodrigo.costa@itec.ufpa.br, {helderp, kassiolsm, cerqueira}@ufpa.br and braun@iam.unibe.ch

***Abstract*—For smart applications, nodes in wireless multimedia sensor networks (MWSNs) have to take decisions based on sensed scalar physical measurements. A routing protocol must provide the multimedia delivery with quality level support and be energy-efficient for large-scale networks. With this goal in mind, this paper proposes a smart Multi-hop hierarchical routing protocol for Efficient VIdeo communication (MEVI). MEVI combines an opportunistic scheme to create clusters, a cross-layer solution to select routes based on network conditions, and a smart solution to trigger multimedia transmission according to sensed data. Simulations were conducted to show the benefits of MEVI compared with the well-known Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol. This paper includes an analysis of the signaling overhead, energy-efficiency, and video quality.**

I. Introduction

In a *smart* Wireless Sensor Network (WSN) [1], the nodes are able to sense environmental conditions in order to plan actions and have a situational awareness of what is happening in the environment and take appropriate decisions.

The proliferation of video applications in smart systems and the demand for new multimedia services in sensor network systems, have fostered the development of Wireless Multimedia Sensor Networks (WMSNs) [2]. The multimedia content has the potential to enhance the level of the collected information, enable multi-resolution views, and avoid false positive alarms, which are expected in environmental monitoring, smart parking, traffic control, smart city and others [2].

In this context, smart communication protocols and algorithms offer a suitable solution to the sensor nodes transferring multimedia data between themselves. Thus, a smart routing protocol is able to improve the energy efficiency, scalability and reliability, and at the same time, enhance the Quality of Service (QoS) and Quality of Experience (QoE) in WMSN applications.

The use of a hierarchical multi-hop architecture with heterogeneous nodes improves the scalability, resilience and energy-efficiency of WMSNs [2]. Where, nodes periodically form clusters, elect a Cluster-Head (CH) and send the sensed data. However, the process of cluster formation should includes a minimal signaling overhead.

A cross-layer approach, based on information of physical, MAC and routing layer, must be used to allow the nodes to perceive the network conditions, and thus be able to dynamically plan, adapt, and take appropriate actions to select the routes. However, the current hierarchical protocols for WMSNs, lack a reliable scheme for selecting routes based on network conditions and energy.

Energy constraints in WMSNs are even stricter than in WSNs, due to the fact that multimedia content (video streaming, image or audio data) creates a huge amount of data to be processed and transmitted. Thus, videos should be sent in a case of an event occurrence.

To address these questions, this paper proposes a smart Multi-hop hierarchical routing protocol for Efficient VIdeo communication over WMSN (MEVI) to overcome the drawbacks mentioned above and allow the transmission of multimedia content with QoS/QoE support.

MEVI adopt the use of a event-based video transmission and relies on two operational modes to enable the nodes to take appropriate decisions with regard to video retrieval and transmission. The transmitted video will be useful to enhance the level of collected information. In fire detection applications videos can be used to avoid false-positive alarms and show the real impact of the fire in the environment.

The main contributions of MEVI are: (i) an opportunistic scheme for cluster formation, by only sending beacon messages; (ii) multi-hop communication between the CHs and Base Station (BS) to assure an energy-efficient communication in large-scale networks; and (iii) a cross-layer scheme to perceive the network conditions and select the routes based on link quality and energy issues.

Simulations were carried out to show the impact and benefits of MEVI in disseminating video content in WMSNs, for large-scale scenarios in comparison to LEACH protocol. The energy-efficiency and video quality level were analyzed by means of well-known QoE metrics, which are Structural Similarity (SSIM) and Video Quality Metric (VQM).

The remainder of this paper is structured as follows. Section II outlines the related hierarchical routing protocols and their drawbacks. Section III describes the proposed routing protocol. Simulations are described in Section IV. Section V, which summarizes the main contributions and results of this paper.

II. Related Works

Low-Energy Adaptive Clustering Hierarchy (LEACH) [3] achieves low energy dissipation and latency without sacrificing application-specific quality. Periodically, the nodes perform cluster creation, CH election, and data collection. LEACH forms clusters by using a distributed scheme.

The main drawback of LEACH, concerns the use of a single-hop communication between CHs and BS, which is not suitable for large-scale WMSNs. Periodic data transmissions are unnecessary, thus causing an ineffective expenditure of energy. Moreover, this approach generates high signaling overhead to create clusters, which decreases the network lifetime and consumes scarce sensor node resources.

Energy Efficiency QoS Assurance Routing in Wireless Multimedia Sensor Networks (EEQAR) [4] introduces a social network analysis to optimize network performance. EEQAR focuses on how to build energy-efficient QoS assurance routing for WMSNs. However, EEQAR does not use a link quality estimator to select reliable routes, generating an extra overhead for route discovery for intra-cluster communication. It does not evaluate the video quality level.

A Power Efficient Multimedia Routing (PEMuR) [5] aims to provide an efficient video communication based on a combination of hierarchical routing protocol and video packet scheduling models. The protocol creates clusters in a centralized way by using a combination of beacon, schedule, advertise, identifier and join messages. The main drawback of PEMuR is that it only uses the remaining energy to find routes (not link quality), which makes the proposal unreliable. Thus, PEMuR does not assure the transmission of videos with QoS/QoE support. The proposal assumes that the BS can communicate with all nodes by using single-hop communication, which is not realistic for large sensor networks. The protocol uses a centralized scheme to create clusters, which increases signaling overhead and decreases network lifetime.

A smart hierarchical routing protocol for multimedia delivery with energy-efficiency and QoS/QoE support should create low overhead to create clusters, multi-hop communication and a cross-layer approach to select the best routes. A multi-hop communication mode with a cross-layer approach to find routes should include information about link quality and energy-efficiency to improve the scalability, reliability and video quality.

III. Multi-hop hierarchical routing protocol for Efficient VIdeo communication (MEVI)

This section outlines a smart Multi-hop hierarchical routing protocol for Efficient VIdeo communication over WMSN (MEVI). MEVI proposes: (i) an opportunistic scheme to create cluster; (ii) multi-hop communication with a cross-layer approach to select routes based on perceived network conditions; and (iii) operational modes to trigger multimedia transmission according to sensed environmental information.

A. Protocol Model Description

MEVI is designed for WMSN applications, which send real-time videos in case of an event occurrence, e.g., temperature higher than $60\,^{\circ}\mathrm{C}$. Thus, it is possible to avoid false-positive alarms and show the real impact of the event in the environment. This scenario is suitable for fire detection in forest areas and smart cities.

MEVI relies on a hierarchical network architecture with heterogeneous nodes, as recommended in [2] to reduce the overall communication overhead, maximize the network lifetime, and improve scalability and reliability. The nodes have heterogeneous capabilities and are divided into the following classes: (i) non-multimedia-aware nodes, restricted in terms of energy supply, processing and memory; and (ii) multimedia-aware powerful nodes, equipped with solar energy source, video camera and higher memory and processing capabilities.

Usually, CHs are used to transmit and receive packets both inside and outside of the cluster, and to perform complex tasks. On the other hand, non-CHs are used for simple tasks, such as detecting scalar physical measurements.

In MEVI, CHs are used for routing, slot allocation, synchronizing non-CH transmissions, multimedia retrieval and data aggregation. The CH should be a powerful node, and thus MEVI considers that multimedia-aware nodes act as CHs. Non-multimedia-aware nodes are source nodes and multimedia-aware powerful nodes are destination nodes. Considering the low cost of the network, the total number of multimedia-aware nodes should be as few as possible.

According to the sensed environmental conditions, e.g. temperature, humidity and others, multimedia retrieval and transmission are triggered. This implies two operational modes, called normal and event mode. There are two thresholds to change the operational mode, named soft and hard thresholds. The soft threshold is triggered when a possibility of an event occurrence is detected. The hard threshold is triggered when an event already happened.

In the normal mode, the CHs are not continuously sending video, with the aim of saving energy and extending the network lifetime. For this mode, the non-CHs are continuously sending the sensed environmental conditions to the BS. If one of the sensed values is higher than a soft threshold, multimedia content is requested.

On the other hand, when an event was detected, such as a sensed value higher than a hard threshold, the nodes do not need to save energy, due to the importance and urgency of transmitting video information. In case of some events the nodes could even be destroyed, e.g. by a fire. Thus, the nodes need to provide as much as possible information to the system administrator.

MEVI considers that data transmission consists of two phases: (i) between the non-CH and its CH (intra-cluster communication); and (ii) between CHs and between CH and BS (inter-cluster communication). The intra and inter-cluster communication comprises a superframe, as illustrated in Figure 1.

The protocol contains a set of parameters for intra-cluster communication, which are as follows: (i) time-slot duration (t_{slot}), which indicates the time interval during which a node can transmit, (ii) superframe size (n), which indicates the number of contained time-slots; and (iii) the total amount of time in a superframe called Round (R).

All the superframes have the same size, which means that they contain the same number of time-slots. The number of slots and their duration depends on the type of application. It is desirable that each node allocates enough slots to satisfy the required application, such as bandwidth and delay.

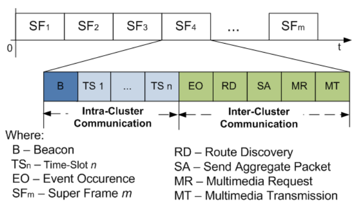


Fig. 1: Superframe structure

B. Intra-Cluster Communication

During this phase, the nodes are creating clusters and the non-CHs send the sensed values to their CH during their time-slot. The details of Intra-Cluster Communication are shown in Figure 2.

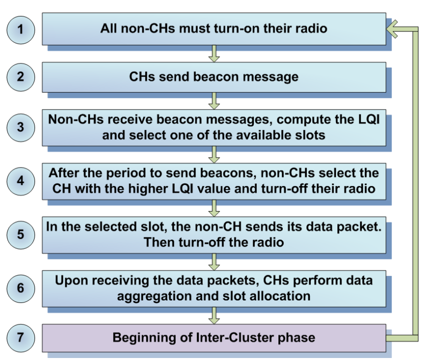


Fig. 2: Overview of the algorithm for cluster formation

Non-CHs remain in sleep mode until the beginning of a new superframe (Step 1), which is started by a beacon message sent by a CH (Step 2). MEVI considers that the beacon contains a slot map, reporting which slots are idle or busy. Compared with other related protocols, the beacon message is a combination of schedule and beacon messages.

Non-CHs must elect a CH as a leader. MEVI relies on a Link Quality Indicator (LQI) as the metric to select the CH. This metric is provided by the physical layer of IEEE 802.15.4, and can be used to improve reliability. The LQI is computed at each received beacon, and the proposal takes into account the degree of variability of the links to select the CH, in particular the history of the last x LQI values (Step 3).

Additionally, a non-CH has to select a slot. Thus, it becomes aware of which slots are idle, by analyzing the slot map contained in a beacon message (Step 3). After the period when CHs are sending beacon messages, a non-CH selects the CH with higher LQI (Step 4). Following this, it waits for its selected slot, and sends the sensed data (Step 5).

MEVI considers that the nodes are creating clusters in an opportunistic way. Since, to the non-CHs allocate a slot, they send only their data packet during the selected slot. This is in contrast to existing routing protocols, where nodes have to exchange beacon, join and schedule messages, before sending their data packets.

The CH receives the data packets and assigns a time-slot according to the following rule (Step 6). If only one node tries to allocate the slot, the slot will be successfully allocated. Otherwise, the CH will assign the slot at random to one of the candidate nodes. After finishing n slots it starts the inter-cluster phase (Step 7).

The non-CHs wait for the next beacon, which will enable them to recognize a valid transmission in the selected slot. If this holds, it means that the slot is allocated, and the non-CH should send the sensed data in the allocated slot. Otherwise, the non-CH must repeat the procedure until a slot assignment is obtained.

The non-CHs change to another CH, only if another CH has a higher LQI value. The non-CHs turn on their radio, only in the period when the CHs send beacons and in their slot. If the CH detects that a slot has not been used for the last y superframes (called idleness of a slot), it will considered as idle.

C. Inter-Cluster Communication

The inter-cluster communication is the period when the CHs and the BS are communicating with each other. This period is used by the CHs to send the aggregate and multimedia data packets to the BS, and the BS can request multimedia content for a CH.

MEVI uses the collected information from the environment to take appropriate decisions with regard to multimedia transmission. Thus, MEVI has two operational modes that change according the sensed environmental value.

If the CH detects the sensed value higher than a hard threshold, such as temperature higher than $60\,^{\circ}C$, the CH should start the event mode by sending an event message in an Event Occurrence (EO) period. The neighborhood CHs forward the message to inform all the network nodes about the event occurrence mode.

After all CHs have become aware of the event occurrence mode, the multimedia transmission (MT) period starts. There, the CH will retrieve and send the multimedia content to the BS using multi-hops.

On the other hand, if the CHs do not receive any event message during the EO period, it means that the network is in a normal mode, which works as follows.

Route Discovery (RD) is the period when the CHs try to find a path to the BS. MEVI exploits a reactive scheme to find routes on demand, to decrease the overhead and improve scalability. Then, the CHs propagate route request (RREQ) and reply (RREP) messages.

Each path has associated a Path Quality (PQ) value to classify the paths. The PQ is computed according to Eq. 1. The equation considers Remaining Energy (RE), LQI, Hop Count (HC) and weight to give a degree of importance to each metric.

$$PQ = \alpha \times \frac{RE}{E_0} + \beta \times \frac{LQI}{maxLQI} + \gamma \times \frac{maxHC - HC}{maxHC} \quad (1)$$

Where, $0 \leq$ PQ ≤ 1, $\alpha + \beta + \gamma = 1$, E_0: Initial Energy, max LQI = 255, and max HC depends on the network diameter.

The path with the highest PQ has better conditions to transmit packets. However, due to network conditions, the links change over time, and it is desirable for the PQ to be periodically updated by the protocol.

To compute the PQ, the CHs should know the remaining energy and the number of hops to reach the destination node. Thus, RREQ and RREP messages have to include additional fields to report these values to the CHs.

Once the CHs have routes, they are able to transmit their aggregate packet to the BS during the Send Aggregate packets (SA) period. Upon the BS receives the aggregate packets, it will analyze the data.

If one of the sensed values is higher than a soft threshold, during the Multimedia Request (MR) period, the BS triggers a route discovery and then requests multimedia content from a CH. When the CH receives the multimedia request message, it will retrieve and transmit the video to the BS.

IV. Performance Evaluation

Simulation experiments were conducted to analyze the performance of MEVI by using the Castalia simulator [6], which is a WSN simulator based on Omnet++ simulator [7]. Castalia includes the implementation of temperature sensor behavior. However, it does not have a video sensor. Thus, Evalvid [8] was adapted to Castalia, to enable multimedia transmissions.

Simulations were carried out and repeated 20 times to have a confidence interval of 95%. The following simulation parameters as shown in Table I were used. The use case of a multimedia-aware fire detection system in an Amazon rainforest was considered.

The Container video sequence with a QCIF resolution was chosen from the Video Trace Library. Container is the video with similar motion and complexity as expected for a fire detection system.

An analysis in terms of the number of nodes that are alive after some rounds and a well-known video quality metric (SSIM and VQM) were performed. The results shown in this Section are the average of network lifetime, SSIM and VQM. The network lifetime has been measured as the time until 10% of the nodes run out of energy.

Figures 3a and 3b show the number of nodes per round that are still alive. The number of nodes alive per round is same for MEVI in both versions, due to the fact that the main difference between them is that the multi-hop version includes a RD between CHs and BS. CHs are supposed to have a solar energy source and during RD the non-CHs are in sleep state.

TABLE I: Simulation parameters

Parameter	Scenario 1	Scenario 2
Field Size	40x40	100x100
Location of Base Station	(20,40)	(50,100)
Transmission Power for Multi-hop	-15dbm	-5 dbm
Transmission Power for Single-hop	-1dbm	0 dbm
Total number of Nodes	100	
Multimedia-aware powerful nodes	25	
Initial Energy (E_0)	10 J	
Temperature Threshold	50 C	
Superframe size (n)	14	
Duration of each Slot (t_{slot})	1 Seg	
Round Duration (R)	30 Seg	
Idleness of a time-slot (y)	5	
Number of LQI values to compute the LQI average (x)	5	
Maximum Hop Count	7	
Video sequence	Container	
Video Encoding	MPEG-4	
Format	QCIF (176 x 144)	

Compared with LEACH, for Scenario 1 and 2 MEVI in both versions increased its network lifetime by 60%, Figure 3a, and Figure 3b, respectively. The reason for this is that in LEACH the CH requires higher transmission power when it sends its packets to the BS, which consumes more energy. Additionally, MEVI reduces the signaling overhead to create clusters and considers two kinds of nodes.

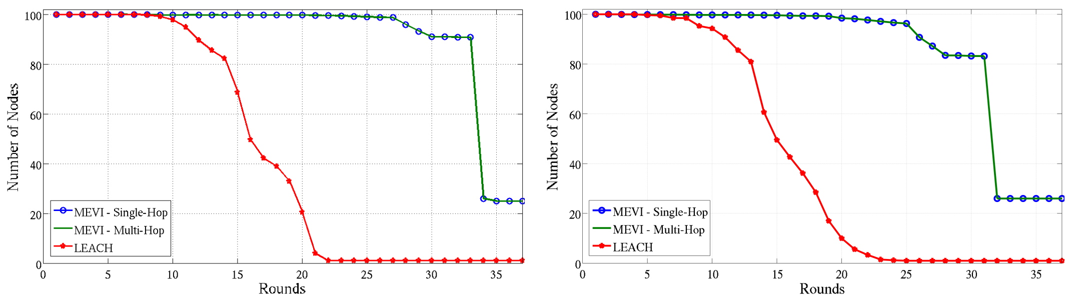
The video quality varies according to the distance from the source to destination. Table II shows the average and Standard Deviation (SD) of video quality metrics (SSIM and VQM) depending on the distance (short, intermediate and longer), considering the videos of Scenario 1.

TABLE II: Video quality according to distance for Scenario 1

Protocols	Short Distances		Intermediate Distances		Longer Distances	
	SSIM	SD	SSIM	SD	SSIM	SD
MEVI Multi-hop	0.89	0.17	0.51	0.17	0.75	0.15
MEVI Single-hop	0.90	0.09	0.77	0.13	0.51	0.05
LEACH	0.90	0.09	0.68	0.16	0.50	0.13
	VQM	SD	VQM	SD	VQM	SD
MEVI Multi-hop	0.49	0.91	2.45	0.88	1.76	0.75
MEVI Single-hop	0.39	0.40	1.27	0.73	2.44	0.26
LEACH	0.39	0.51	1.04	0.81	2.45	0.46

For short distances, the videos have a similar quality regardless of the protocols, since the nodes are near to the BS and use few hops. For intermediate distance, the MEVI multi-hop version has an inferior performance. This is because MEVI uses intermediates nodes to forward the packets, and there are cases in which the buffer size of intermediate sensor nodes exceeds the capacity limit. In such a case, each sensor node decides which packets should be dropped.

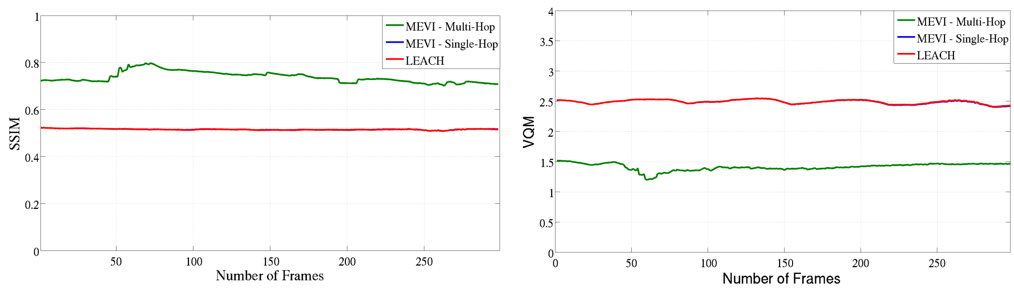
However, for long distances, multi-hop has better performance, as expected for real large-scale scenarios, e.g. smart cities and environmental monitoring. This improvement is due to the fact that MEVI uses multiple hops, with a cross-layer



(a) Nodes that still alive for Scenario 1

(b) Nodes that still alive for Scenario 2

Fig. 3: Average of network lifetime



(a) SSIM of videos 36 m distant from BS

(b) VQM of videos 36 m distant from BS

Fig. 4: Video quality level for Scenario 1

solution to select reliable routes. The selected routes are based on network conditions, i.e., LQI, remaining energy and hops.

For single-hop protocols, all CHs use the same transmission power to reach the BS, which is higher than used for the MEVI multi-hop version. It is important to highlight that for Scenario 2, the single-hop protocols are not able to reach the BS, and thus send multimedia packets to the BS with a greater degree of reliability for distances longer than 50 m.

For Scenario 1, the video quality of a specific node (36 m distance from BS) is analyzed by taking the average of SSIM and VQM for each frame that composes the video, as shown in Figure 4a and 4b, respectively. Single-hop protocols have almost the same video quality level, since the transmitting nodes use the same transmission power at the same distance. However, MEVI multi-hop increases the video quality by 20% for SSIM and 40% for VQM. This is due to the fact that the proposed cross-layer solution selects reliable paths based on perceived network conditions.

V. Conclusion

This paper presents MEVI, a smart routing protocol that aims to provide efficient multimedia delivery. MEVI combines an opportunistic scheme to create clusters with a minimal overhead, and a multi-hop communication between the CH and BS. For route selection, a cross-layer solution is proposed that is based on network conditions. Additionally, the nodes capture and send video in accordance with the environmental information that has been collected.

Simulations were carried out to show the benefits of MEVI. It was found that the proposal increases the network lifetime by at least 60% for short and longer network field size. The quality of the received video is increased by at least 20% for small field sizes. For large field sizes, MEVI still delivers the video, rather than a single-hop solution that is not able to perform multimedia delivery.

VI. Acknowledgment

This work is supported by CNPq, FAPESPA and FADESP.

References

[1] F. Zhao and L. Guibas, “Wireless sensor networks,” *Communications Engineering Desk Reference*, p. 247, 2009.

[2] I. Almalkawi, M. Guerrero Zapata, J. 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] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-efficient communication protocol for wireless microsensor networks,” in *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences, 2000.* IEEE, 2002, pp. 10–pp.

[4] K. Lin, J. Rodrigues, H. Ge, N. Xiong, and X. Liang, “Energy efficiency qos assurance routing in wireless multimedia sensor networks,” *IEEE Systems Journal*, vol. 5, no. 4, pp. 495 –505, dec 2011.

[5] D. Kandris, M. Tsagkaropoulos, I. Politis, A. Tzes, and S. Kotsopoulos, “Energy efficient and perceived qos aware video routing over wireless multimedia sensor networks,” *Ad Hoc Networks*, 2011.

[6] A. Boulis, “Castalia, a simulator for wireless sensor networks and body area networks, version 2.2,” August 2009.

[7] A. Varga, “The OMNeT++ discrete event simulation system,” in *Proceedings of the European Simulation Multiconference (ESM 2001)*.

[8] Evalvid, “Evalvid - a video quality evaluation tool-set,” available at:http://www2.tkn.tu-berlin.de/research/evalvid/fw.html accessed at Jan. 2012.