Content Relevance Opportunistic Routing for Wireless Multimedia Sensor Networks

Petros Spachos*, Angelos K. Marnerides§ and Dimitrios Hatzinakos*
*Department of Electrical and Computer Engineering, University of Toronto, Toronto, Canada
§InfoLab21, School of Computing & Communications, Lancaster University,Lancaster, UK
E-mail: {petros,dimitris}@ece.utoronto.ca, a.marnerides2@lancaster.ac.uk

***Abstract*—Wireless Multimedia Sensor Networks (WMSNs) are considered as one of the most prominent infrastructures for human-centric multimedia applications due to the wide availability of low-cost hardware such as microphones and CMOS cameras. By virtue of the energy limitations on sensor nodes alongside the explicit highly demanding bandwidth requirements of real-time multimedia applications, these particular networks foster a set of non-trivial challenges that need to be confronted. In this paper we define a level of relevance in regards with the content of a multimedia packet and we further introduce a dynamic routing protocol that optimizes the overall network performance in terms of energy efficiency and packet delay. We present the design, implementation and applicability of our Content Relevance Opportunistic Routing (CROR) protocol under experimental results that show an increase in network lifetime of up to 20% compared with traditional routing.**

I. INTRODUCTION

Undoubtedly, recent years have shown a growth of interest from the research community towards the design and deployment of Wireless Multimedia Sensor Networks (WMSNs). These networks evolved as an attractive domain since they empower properties such as self-organization and at the same time require low-cost hardware that is widely available in the market. WMSNs are composed by resource-constrained self-organizing wireless sensor nodes where some or all of them are endowed with a low-power camera for a series of innovative multimedia sensing functions [1]. Information retrieved from those networks significantly improves the capabilities of sensor surveillance and monitoring infrastructures that serve a big number of deployed human-centric applications [2].

There is a plethora of applications that offer monitoring and surveillance-based services such as digital CCTV, person location tracking, advanced health care delivery and automated assistance services for elderly people where inexpensive and easily deployed WMSNs seems to appear as the ideal ubiquitous solution [3]. Nevertheless, due to the high bandwidth requirements alongside their intrinsic prioritization and sensing aspects for real-time processing, such human-centric applications engage several challenges. Despite the fact that inch scale sensor devices have been designed to work unattended with limited computational capabilities and low power requirements for long periods of time, there is still a greater concern regarding the lifetime of a sensor network. In comparison with rechargeable portable devices, such as cellular phones and laptops, sensor node battery recharging or replacement is, in the majority of cases, infeasible or impossible. Thus, the lifetime of any individual node, and as a consequence, of the whole network, is decided by how the limited amount of energy is utilized.

In parallel with the optimal energy management issue, there also exists the demanding requirement with respect to the adequate communication-wise operation and performance of the WMSNs. Consequently, packet delay is crucial to address in order to guarantee an acceptable and optimal level of reliability, availability and scalability of these networks. Therefore, it is of critical importance for data routing schemes to confront the aforementioned properties by ensuring a robust energy management scheme that would minimize packet delays. At the same time and based upon the explicit nature of WMSNs, it is also necessary to map the prioritization of multimedia packets that traverse throughout the sensor links and comply with their Quality of Service (QoS) requirements. In [4], a QoS routing scheme for wireless multimedia ad hoc network was presented and in [5], an energy-aware MAC and routing mechanisms was designed specifically for WSNs to reduce energy consumption and provides QoS guarantees. In [6] a statistical QoS routing was introduced. A fully distributed scheduling scheme for video streaming over multi-channel multi-radio multi-hop wireless networks was presented in [7].

Given the composite problem space derived by WMSNs, this paper proposes a content-based, opportunistic routing scheme that aims to confront the majority of the aspects described above. As indicated by many studies, the properties of opportunistic routing can alleviate the problem and further improve several QoS domains [8]–[12]. Thus, we extend a simple data relevance scheme [13], and introduce a *Content Relevance Opportunistic Routing (CROR)* protocol that overarches the trade-off between packet delay, energy efficiency and content-based packet prioritization. The manifestation of our protocol heavily depends on the orchestration of a network addressing formulation that performs a selection criterion by considering relevance levels as derived by the explicit nature of a packet content (e.g. packet type, priority level) alongside the energy resources and computational capabilities of a given sensor. Moreover, we use a practical link model via assigning

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a Packet Error Rate (PER) over each available link whilst utilizing cognitive radio for applying a collision avoidance scheme. The following highlights our contributions:

- We introduce a *Content Relevance Opportunistic Routing, (CROR)* protocol for WMSNs that addresses the demanding requirements of network performance, application-specific packet prioritization and energy efficiency.
- We Propose a generic *Packet Relevance Level Scheme, (PRLS)* that may be easily configured for the needs of any human-centric QoS prioritization in WMSNs.
- We improve the scalability and reliability aspect of prioritized multimedia content transmissions since the proposed protocol may adequately adapt whilst the density of a given WMSN increases.
- We evaluate the performance of CROR. Simulation results have shown an extend up to 20% to the lifetime of a WMSN in comparison with traditional routing protocols under stressful human-centric multimedia content.

The remainder of this paper is organized as follows: The system model is described in Section II. Section III briefly introduces the basic formulations of our proposed CROR protocol. Section IV is the performance evaluation followed by the conclusion in Section V.

II. SYSTEM MODEL

This section provides an overview of the system model's basic functionality. In particular, there is a brief introduction to the addressing performed on the sensor nodes, followed by the wireless link model that we apply. Finally, this section also illustrates the *Packet Relevance Level Scheme, (PRLS)* that is considered as one of the crucial components within the routing formulation proposed in this paper.

A. Network address mechanism

The network address of each sensor node in the network is subjected to a delivery criterion and is related to the distance from the destination node. Given the address of a node i and the address of the destination node dst, the delivery criterion $c_{i,dst}$ should be locally obtained. In the proposed protocol, the destination node broadcasts identity advertisement packets towards every sensor node in the network. These packets have the delivery criterion field $c_{dst,dst}$ equals to zero. On the reception of a packet, every sensor node i updates the delivery criterion field according to its hops from the destination $c_{i,dst}$. At the end of this procedure, every node knows its delivery criterion. As the network scalability changes, the nodes can update their delivery criterion locally. If a node joins the network, its logic address can be estimated by acquiring the logic address of the nodes in its neighbor area. If a node stops working or leaves the network or even if the source node changes, the network addresses of all the nodes remain the same. Only if the destination node changes the initialization phase should take place again.

This is crucial for human-centric networking where the node that needs to transmit information moves in different locations, hence, the source node of the network changes. If the destination node switches location, then the procedure should take place again. Nonetheless, this particular network address model was followed due to the fact that in a WMSN there is one destination, usually a monitoring room. This destination is static while a number of sources can be in different locations.

B. Wireless Link Model

Every packet transmission over the wireless link is subjected to a Packet Error Rate (PER). To simulate a realistic channel model for lossy WMSNs with Binary Phase-Shift Keying (BPSK) without channel coding, the $\hat{PER}(i)$ is:

$$\hat{PER}(i) = 1 - \Big(1 - Q\Big(\sqrt{\frac{2P_t(i)\cdot \hat{G}(i)}{\sigma_n^2}}\Big)\Big)^{F_d}, \qquad (1)$$

where F_d is the size of the data packet, σ_n^2 is the noise power, P_t is the transmission power, $Q(x) = \frac{1}{\sqrt{\pi}} \cdot \int_{\frac{x}{\sqrt{2}}}^{\infty} e^{-t^2} dt$ and

$$\hat{G}(i) = A \cdot \hat{D}_s(i)^{-n}, \qquad (2)$$

where $\hat{D}_s(i)$ is the distance between the sender node s and the next node i, A is a constant, and n is wireless channel path loss component.

From Eq.1, it can be inferred that P_t is crucial for the network connectivity. When P_t is low, the network might have low or no connectivity. On the other hand, a high P_t may lead to waste of the limited energy of the nodes. Moreover, the number of collisions between neighbouring nodes will increase. Within our proposed *CROR* protocol, the power P_t was carefully selected in order to satisfy the WMSN scenario.

C. PRLS: Packet Relevance Level Scheme

We consider the *Packet Relevance Level Scheme (PRLS)*, as a core component for the overall performance of the proposed protocol. A number of relevance schemes have been proposed for different network types [14]. Similarly with the labeling existing in QoS schemes (e.g. MPLS), in our scheme a field within a packet's header is labeled with its relevance from a source node leading an indication to the neighbouring nodes regarding the importance of the packet. However, at this stage we have to clarify that our proposed *PRLS* scheme can be tuned according to the explicit nature of a multimedia human-centric environment and the exemplar insight given in this work is simply illustrating the intuitive aspect of this generic scheme. Therefore, an irrelevant, low, medium, high or maximum relevance level packet should be adjusted based on the QoS requirements imposed by the operator(s).

For instance, in a scenario where a packet holds a low relevance level, it will be transmitted through nodes nearby the transmitter since time delay is not crucial for this packet. As an example may be considered, a human-centric network composed of smart phone devices, where packets related with games and advertisements [15], can be classified as of low relevance or irrelevant. Advertisement notifications can be delivered with a delay to the user, while the energy levels of the network should not be decreased sufficiently with an increase of the advertisement volume.

In *PRLS*, a packet with a medium relevance level, will be transmitted to the destination over one of the available paths that holds the minimum number of hops along with sufficient energy to the transmitting nodes. In most cases the path is not necessarily the shortest but due to the energy constraint it is considered reliable with respect to service. Paths that have not been used frequently and are usually defined by nodes with unused energy, can deliver the packet on a minimum delay and are preferred over the default shortest path. By virtue of the opportunistic and reactive path discovery embedded within the introduced protocol, the number of these paths increases with respect to the increment of the network's density. In general, medium relevance level packets may be labeled as those that carry information and are considered as regular and do not trigger or require any "on the fly" event processing mechanism. Examples of such information may be image, temperature or pressure data on monitoring environments or social media data of smartphones within a WMSN.

On the other hand, a packet with a high relevance level is required to be delivered at the destination node with the minimum end-to-end delay. The nodes that are on the shortest path or close to it and are available for immediate transmission will be used. Since the nodes availability and the network condition varies over time, different shortest paths consisting of different nodes will be available in different time frames. At the same time, if another packet with smaller relevance level requires transmission, it is placed in a prioritization queue and gets served as soon as the rest of the packets with higher relevance levels are transmitted. Thus, the higher the relevance level, the higher the priority. Hence, in the scenario of images or video stream packets that captured a crime event within a surveillance sensor network should be delivered promptly to the central station and in parallel the network should have sufficient energy to deliver those packets. Similarly, a video of the breaking news or the current traffic condition is of the highest importance and should be delivered to the smartphone user on time and over reliable links. Table I shows the five types of relevance levels as implemented in our introduced protocol accompanied by exemplar labeling that could be used to human-centric mobile sensor networks (e.g. with smartphone devices). Although the depicted examples are focused on specific scenarios, we again clarify that the proposed scheme may be easily tuned for any WMSN scenario where packets hold different QoS requirements.

Level L_k	Relevance	Example
0	Irrelevant	General advertisements.
1	Low Relevance	Notification from social media.
2	Medium Relevance	Regular video stream, image transmission, chat.
3	High Relevance	Event notification, real time game engines notification.
4	Maximum Relevance	Breaking news, weather/ traffic alerts.

TABLE I: Relevance levels and example of packet classification arriving on a smart phone device.

III. CROR: CONTENT RELEVANCE OPPORTUNISTIC ROUTING

The proposed *Content Relevance Opportunistic Routing (CROR)* for WMSNs is a reactive opportunistic protocol due to its ability to discover routes only when desired. Thus, an explicit route discovery process is initiated only when needed. Hence, in *CROR* the destination node triggers and terminates the route discovery process when a routing path has been established. The established path is maintained via a preserving procedure until it is no longer available or requested.

Within *CROR* there is the capability of maintaining multiple paths between a source/destination pair and packets can follow any of those paths after considering dynamic network condition changes. We consider as varying network conditions those of interference, channel and relay node availability and energy levels. Moreover, due to the probabilistic choice of the relay nodes, the protocol is able to evaluate different routing paths continuously and select them based on the changing network condition in every time slot. Overall, the proposed protocol is composed by three phases that we present next.

A. Neighbor discovery process

The first phase includes a neighbor discovery process. We assume that every sensor node i in the network knows its relative location, hence it can categorize the nodes around it into *neighbor node set* A_i, and *candidate node set* K_i.

Neighbor node set A_i of node i, is a set of all the nodes in the transmission range R, of node i:

$$A_i = \{j \in S \mid d_{i,j} \leq R\}, \; i \neq j \tag{3}$$

where S is the set of all the nodes in the network, $d_{i,j}$ is the distance between node i and node j and R is the transmission range of the node.

Candidate node set K_i of node i, is a set of those nodes that are in A_i and they are closer to the destination node dst than the transmitting node i. Candidate node set is a subset of neighbor node set, $K_i \leq A_i$ and can be defined as:

$$K_i = \{j \in A_i \mid d_{j,dst} \leq d_{i,dst}\}, i \neq j \tag{4}$$

The neighbor discovery process takes place at the initialization phase of the network and it is initiated by the destination node dst. This node floods a number of small packets to its neighbor node set A_{dst}. The packets have a field with the number of hops from the destination. On the reception of a packet, every node in the network checks this field and update the delivery cost towards the destination accordingly.

These initial packets help a node i not only to find the number of hops from the destination $c_{i,dst}$, but also to find the number of neighbor nodes A_i. Different neighbor nodes from A_i set will forward the same packet to node i.

This process is over when there are no new nodes to forward the packets. After the end of this process, the nodes knows the necessary information for A_i and K_i sets and can start the data packet transmission. Periodically, when the nodes do not participate in data transmission, they can exchange small packets and update these two important metrics.

B. Packet relay mechanism

Subsequent to the neighbor discovery process, there is the packet transmission process which follows a packet relay mechanism. There are four types of packets: *Request To Send (RTS)*, *Clear To Send (CTS)*, *DATA*, and *Acknowledgement (ACK)*. Every packet transmission is subject to the *PER*, as in Eq.1.

Every node in the network can be the source node. When a node i needs to transmit a DATA packet, it first tries to find an available neighbor node from its candidate set K_i, through a *RTS/CTS* handshake. The node i floods a *RTS* packet and waits for the first *CTS* response from any node in the K_i set. Since the node floods the packet over the wireless medium, which is an open medium, every neighbor node in its A_i set might receive the *RTS* packet. If a node which belongs to A_i and not to K_i set replies to the transmitter, the transmitter will ignore the response. The transmitter node i will wait for time T_{RTS} before it considers the *RTS* packet was lost and retransmits it. The time T_{RTS} before the node retransmits data is equal to:

$$\begin{aligned} T_{RTS} = & \left(\frac{RTS_{size} + CTS_{size}}{T_{tr}} + (2 \times T_{pd})\right) \times \\ & \times \exp(A_i) \times C_0 + SIFS \end{aligned} \qquad (5)$$

where RTS_{size}/CTS_{size} is the size of *RTS/CTS* packet, T_{tr} is the transmission rate, T_{pd} is the propagation delay needed to reach a node placed at the border of the transmission range R of the transmitter and $SIFS$ is the *Short Interframe Space*, the small time interval between the *RTS* and *CTS* transmission.

After time T_{RTS} the transmitter assumes that the *RTS* packet was lost and it retransmits it. In the proposed protocol, when the number of the neighboring nodes A_i increases, T_{RTS} also increases in such way that the transmitter will wait longer for a response. In this way, there is enough time for all the neighboring nodes to reply to the *RTS* before a retransmission of the packet. Thus, energy is saved from reducing retransmissions.

Some nodes from the K_i set will receive the *RTS* and will reply with a *CTS*. In the proposed *CROR* protocol, on the reception of a *RTS* packet a node j will wait for time:

$$T_{backoff} = ((\overline{L} - L_k) \times \log(d_{i,j})) \times C_0 + C_1 \times SIFS \qquad (6)$$

where $\overline{L}$ is the mean of the explicitly applied *PRLS*, L_k is the packet relevance level k of the current packet, d is the distance between the communicating nodes i and j, and C_0 and C_1 are constants defining the response timing of a node and may be tuned according to the particular QoS requirements of a given network.

Figure 1 shows an example of the $T_{backoff}$ under different distances between the communication nodes and packets with different *PRLS* values. As shown, while the *PRLS* value increases, the $T_{backoff}$ decreases for the nodes at a distance. Furthermore, for *PRLS* values higher than the mean, nodes that are in greater distance from the transmitter will wait less time and target to reply first. For lower than the mean *PRLS* values, nodes that are closer to the transmitter will try to reply first, since these nodes have smaller $T_{backoff}$.

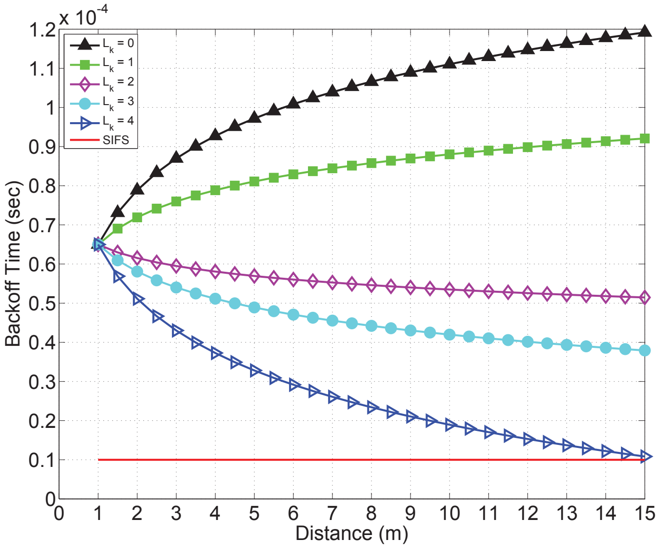

Fig. 1: The $T_{backoff}$ for nodes in different distances from the transmitter and for packets with different *PRLS* values L_k, following Eq.6 for $C_0 = 10^{-5}$ and $C_1 = 7$.

When $T_{backoff}$ terminates, the node j will respond with a *CTS* packet. On successful reception of a *CTS* packet, the transmitter will forward the *DATA* packet to the node that replied first with a *CTS* and will ignore any of the consequent *CTS* packets for the same DATA packet. The transmitter then will wait for an *ACK* of the packet. Since the *CTS* transmission is also subjected to the *PER*, some packets might be lost.

Given Eq.6, the selection criterion of the next relay node is a combination of the distance from the destination and the packet *PRLS* value. When the *PRLS* value decreases, it implies that the closer a node is to the transmitter the smaller the $T_{backoff}$. Hence, neighboring nodes that are close to the transmitter will serve packets with low *PRLS* value and the required number of hops will be higher. If a packet with a higher *PRLS* needs to be transmitted through the same nodes, the nodes will store all the packets in their buffer and will prioritize their transmission according to their *PRLS* value. The higher the relevance, the higher the transmission priority.

On the other hand, packets with high *PRLS* value will be forwarded to nodes that are located close to the limits of the transmitter's transmission range. These nodes will forward the packets to the destination in less number of hops than any other available node at the time. If a packet with lower *PRLS* value needs to be transmitted through the same nodes, it will have to wait for any other packet with higher *PRLS* to be transmitted first. In parallel, each intermediate node follows the same packet transmission process where consequent packet transmissions might use different paths and different channels. Overall, the aforementioned process continues until all packets reach the destination node.

C. *Route maintenance*

Localized flooding is performed infrequently in order to keep all the information about the different routing paths updated. Sensors that are not participating in any transmission at that time, help with the collection of maintenance information. This process also helps to check if any new node joins the network or if they run out of energy and stop operating. The nodes can then update their neighbor node metric.

IV. PERFORMANCE EVALUATION

The proposed protocol is compared with traditional routing in terms of network lifetime, energy distribution and average end-to-end packet delay and presented herein. Our experimentation was achieved after using a version of a prototype sensor node [16] and OPM15 boards [17], shown in Fig.2 and 3, and aimed at comparing our *CROR* over traditional routing. The studied area is the 4^{th} floor of the *Bahen Centre for Information Technology (BCIT)* building located at the University of Toronto. For the experimentation 40 nodes were used and uniformly distributed over the studied area.

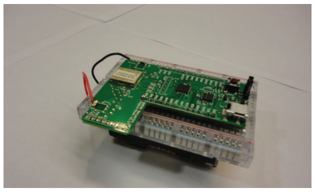

Fig. 2: Prototype.

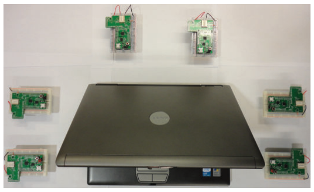

Fig. 3: Experiment boards.

Traditional routing utilizes nodes that can deliver the packet over reliable links (i.e. links with $PER < 10\%$) and with the minimum number of hops. On the other hand, the proposed *CROR* protocol tends to use links with $PER < 80\%$. In addition, it checks the link performance and availability for every packet transmission where traditional routing has a prefixed path for all the transmissions. The experimentation took place 5 times with raw data, equally distributed among all the levels of the proposed *PRLS*. We have used two different sources and one destination and the communication parameters between the experiments were similar.

1) Network lifetime: Network lifetime is the time interval between the first packet transmission until the first node failure due to battery depletion.The sensor nodes operating on 3 AA batteries with $1000mAh$ capacity, hence each sensor node will have an initial energy of:

$$\begin{aligned} E_{init}\ (J) &= capacity(Ah) \times voltage(V) \times time(s) \\ &= 1 \times 3 \times 1.5 \times (60 \times 60) = 16200J \end{aligned} \tag{7}$$

As indicated by Fig. 4, traditional routing forwards all the packets through the same routing path having the nodes on this path keep transmitting and eventually they all run out of energy. Consequently, this approach leads to a decrease of the network lifetime. On the other hand, the *CROR* protocol has a better performance. The main reason is that *CROR* utilizes the shorter paths only for packers with high *PRLS* values. For packets with low *PRLS* value, nodes which have not participated in many packets transmissions have high energy levels, therefore they are preferred. As the network density increases there are more neighboring nodes on the best path from the source toward the destination, thus extending the network lifetime.

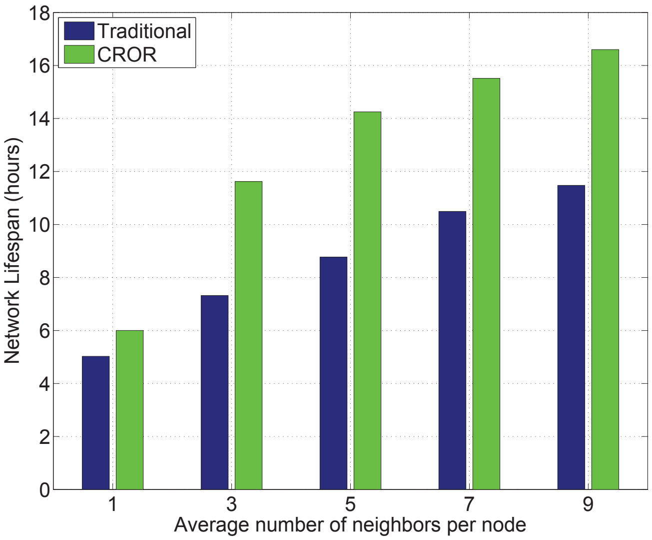

Fig. 4: Network lifetime under different network density.

2) Energy distribution: Energy distribution refers to the energy consumption of each node in the network. Overall, we have measured the energy consumption on each node after the end of each of the 5 experiments.

Figure 5 and Figure 6 depict the energy distribution for the two protocols. Traditional routing uses the same nodes for all the packet transmissions. Consequently, only 9 nodes in our experiments have consumed energy. It is evident that the energy distribution is better with the *CROR* protocol since it allows the utilization of more used sensor nodes for different packet transmissions. Only the different source nodes and the destination node have high energy consumption. Eventually, the remaining nodes have consumed almost equal energy. The proposed approach tries to exploit all the available nodes at the network and leads to a much more efficient routing scheme in terms of energy distribution.

3) Average end-to-end packet delay: In our experiments a number of 600 packets with *PRLS* values 0, 2 and 4 were transmitted from different sources to the destination for each network density and we have calculated the average end-to-end packet delay as indicated in Fig.7.

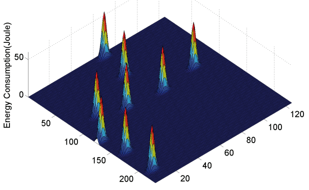

Fig. 5: Traditional Routing.

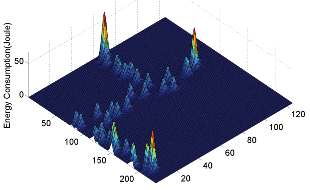

Fig. 6: CROR.

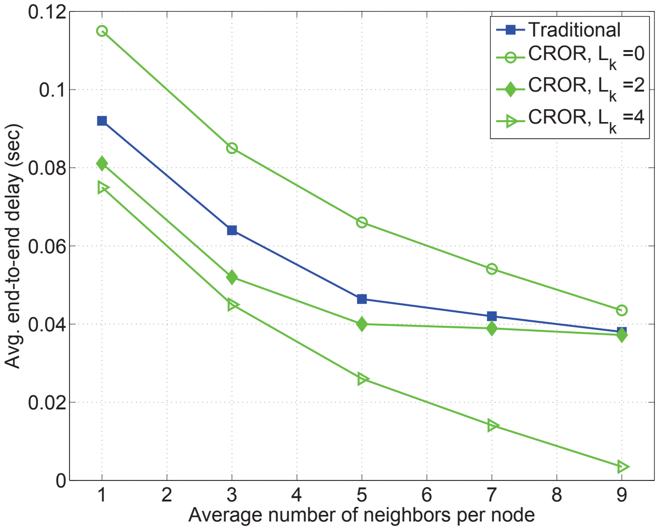

Fig. 7: Average end-to-end packet delay under different network density.

Traditional routing has the same performance for every packet transmission whereas the *CROR* protocol does not perform as well as traditional routing for packets with low *PRLS*. The main reason lies with the fact that this approach tries to conserve energy to transmit packets with higher *PRLS* values. Hence, it tends to use nodes that have not been used that often for packet transmission. These nodes lead to paths with more number of hops than traditional routing and as a consequence the average end-to-end packet delay is higher than in traditional routing. Therefore, while the network density increases, the difference between the two approaches is smaller since the *CROR* protocol can discover more neighboring nodes that can lead to paths with similar performance as traditional routing. The performance of the two routing schemes for packets within the medium *PRLS* values is close to similar. Our *CROR* protocol urges to find any path and not the shortest one towards the destination under an opportunistic nature. Hence, it can deliver the packets over nodes and links that traditional routing does not use. These links might be unreliable for traditional routing, while it can be reliable for the *CROR* at the time of the transmission, leading to a path with less number of hops. On average, the performance for these packets is similar. Finally, for maximum *PRLS* labeled packets, the introduced *CROR* holds a much better performance than traditional routing. This outcome is mainly related with the opportunistic aspect of this protocol since it takes advantage of the broadcast nature of wireless communications. In addition, the *CROR* manages to deliver the packets over any available node at the time of the transmission. Consequently, these nodes can deliver the packet in less time to the destination, leading to a significant smaller average end-to-end packet delay.

V. CONCLUSION

In this work we introduce a *Content Relevance Opportunistic Routing (CROR)* protocol for WMSNs, that achieves optimal energy management as well as end-to-end packet delay minimization. The proposed protocol heavily depends its operation on a node selection criterion and a *Packet Relevance Level Scheme (PRLS)*, that we also introduce. We show that our generic *PRLS* may be easily tuned in order to address prioritization as required by intensive real-time multimedia content. In parallel, we exhibit that while the network density increases, our protocol overcomes traditional routing and allows optimal energy management whilst increasing the network lifetime up to 20%. Via the experimental outcomes provided herein, we argue that our proposed *CROR* protocol promotes a promising approach for ensuring acceptable QoS on highly intensive real-time multimedia applications over WMSNs.

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