IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received April 24, 2018, accepted May 15, 2018, date of current version June 20, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2841821

Green Wireless Video Sensor Networks Using Low Power Out-of-Band Signalling

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This work was supported in part by the Project TEC4Growth-Pervasive Intelligence, Enhancers, and Proofs of Concept with Industrial Impact under Grant NORTE-01-0145-FEDER-000020 and in part by the Project Symbiotic Technology for Societal Efficiency Gains: Deus ex Machina under Grant NORTE-01-0145-FEDER-000026, both financed by the North Portugal Regional Operational Programme (NORTE 2020), through the PORTUGAL 2020 Partnership Agreement, and the European Regional Development Fund.

ABSTRACT The availability of low cost networked wireless devices and video cameras is enabling wireless video sensor networks (WVSNs), which can be used in scenarios such as healthcare, agriculture, smart cities, intelligent transportation systems, and surveillance. These scenarios typically require that each node sends a video stream to a server located in the cloud. The IEEE 802.11 is considered a suitable technology for transmitting video wirelessly, as it supports high data rates. However, when using a multi-hop topology to extend the IEEE 802.11 coverage, the IEEE 802.11-based WVSNs suffer from three problems: low network capacity, throughput unfairness, and energy inefficiency. To overcome these problems, we propose a holistic solution, named Green wiReless vidEo sENsor NEtworks uSing out-of-band Signalling (GREENNESS). GREENNESS combines a node polling mechanism with the use of out-of-band signaling over a low power radio to signal when a video sensor should switch ON and OFF its IEEE 802.11 interface, thus saving energy. The results obtained for random network topologies show that GREENNESS can achieve energy savings up to 92%, and improve network capacity and throughput fairness when compared to state of the art CSMA/CA-based WVSN solutions.

INDEX TERMS Energy-efficiency, low power radio, network performance, out-of-band signaling, wireless video sensor networks.

I. INTRODUCTION

The outburst of connected low-cost devices [1] such as Raspberry Pi Zero, combined with the availability of affordable video cameras, is contributing to the emergence of Wireless Video Sensor Networks (WVSNs) as part of the Internet of Things [2]. WVSNs enable a range of new applications in fields such as healthcare, agriculture, smart cities, intelligent transportation systems, and surveillance [3]. An example of a smart city application is the SmartSantander project in Spain, which involves the deployment of over 3,000 sensor and relay nodes in the Santander city, supporting environmental monitoring, outdoor parking area management, and gardens irrigation [4]. Most of these devices have a Linux distribution, with the standard Transmission Control Protocol / Internet Protocol (TCP/IP) stack, which enables a Wireless Video Sensor (WVS) node to get connected to peer WVS nodes and send information to servers in the cloud [5], [6].

In these scenarios, there is usually the requirement of sending the video streams to a server located in the cloud. As shown in Fig. 1, all the nodes of the Wireless Video Sensor Network (WVSN) send the video streams to the gateway, which in turn forwards them to the server. A single-tier WVSN is adopted since the WVSs are homogeneous and the storage is located in the cloud. WVSs are fixed and the data delivery model is continuous time-driven from the WVS to the cloud server [7]. The video stream should be transmitted reliably to the sink with time constraints and minimal packet loss. Video streaming design aspects related to Quality of Service (QoS), fault-tolerance, and Quality of Experience (QoE) are out of scope of this paper. IEEE 802.11, also known as Wi-Fi (the two terms will be used interchangeably in this article), is a suitable technology for transmitting video wirelessly, as it is ubiquitous and supports high data rates, especially the new variants IEEE 802.11ac and IEEE 802.11ad.

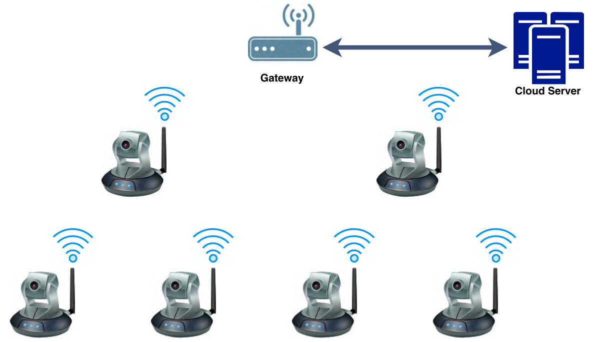


FIGURE 1. GREENNESS reference scenario.

Nevertheless, the use of IEEE 802.11 in single-radio, multi-hop topologies leads to three major problems: low network capacity, throughput unfairness, and energy inefficiency [8].

IEEE 802.11 uses the Carrier Sense Multiple Access – Collision Avoidance (CSMA/CA) mechanism to control the access to the medium. When used in multi-hop networks, this mechanism leads to low network capacity, due to the presence of hidden nodes [9]; using the Request to Send / Clear to Send (RTS/CTS) mechanism does not solve the problem in mesh topologies and creates the exposed node problem. Also, the multi-hop nature of a WVSN brings up throughput unfairness [10] and the nodes closer to the gateway tend to monopolise the medium making the other nodes to starve. Finally, energy inefficiency is a consequence of 1) the low network capacity of CSMA/CA in multi-hop topologies, since packets have to be retransmitted several times, and 2) the fact that the WVS network interfaces are always ON, even when not transmitting or receiving any data.

Motivated by these three major problems, we propose GREENNESS, a holistic solution for green multi-hop WVSNs. GREENNESS aims at reducing energy consumption, improving network capacity, and throughput fairness of multi-hop WVSNs when compared to CSMA/CA. This article presents an extended version of the work published in [8], [9], and [11]. In [8] we presented the initial concept using an FM radio to signal when a video sensor should switch ON and OFF its IEEE 802.11 interface and validated that it was possible to save energy for a set of regular network topologies. In [9] we developed the scheduling algorithm, deployed it on a real testbed with 7 WVS nodes, in order to test the proposed solution in a real environment, and presented the achieved energy savings and network performance. In [11] we compared the simulation and testbed results and presented an initial version of the traffic-aware node scheduling algorithm. Addressing the same topic and having the same goal, this extended version adds to our previous work a) the support of different out-of-band control radios, b) an enhanced traffic-aware node scheduling algorithm, c) the WVSN active topology collection mechanism, and d) a comprehensive evaluation of the GREENNESS solution for random network topologies.

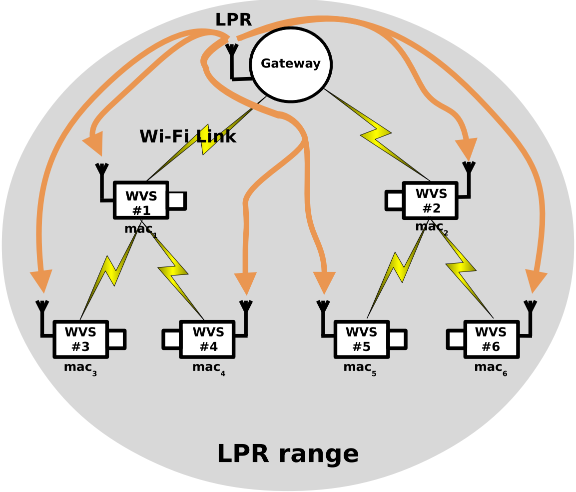


FIGURE 2. The GREENNESS concept, with the node scheduling mechanism running over the LPR control channel illustrated by the arrows in orange.

GREENNESS combines a node polling mechanism, such as the one defined in [12], with the use of out-of-band signaling over a Low Power Radio (LPR) integrated into each WVS node. Fig. 2 presents the GREENNESS concept, considering a multi-hop WVSN with an LPR installed in each WVS and in the gateway. The registration of each WVS node in the gateway enables the collection of the WVSN topology. Based on the collected WVSN topology, the gateway polls each node using the LPR, such as Frequency Modulation – Radio Data System (FM-RDS) or IEEE 802.15.4g, as an out-of-band control channel, and enables the transmission of packets through the Wi-Fi data channel. This mechanism guarantees a transmission opportunity for every single node, avoiding collisions and promoting throughput fairness [12]. GREENNESS uses the LPR as an out-of-band control channel to improve the energy efficiency of the WVSN; Wi-Fi radios of the WVSs are turned OFF when they are not transmitting data. GREENNESS can work with any routing protocol, but in this paper we assume that the Wi-Fi network Infrastructure eXtension (WiFIX) routing protocol [10] is used.

Our main contribution is the GREENNESS solution. Featuring a low power out-of-band control channel and a traffic-aware node scheduling mechanism, it enables significant energy savings while improving network capacity and throughput fairness when compared to CSMA/CA-based WVSNs.

The rest of this paper is organized as follows. Section II presents the related work. Section III describes the GREENNESS solution, namely the traffic-aware node scheduling mechanism and the candidate wireless technologies for implementing the control channel. Section IV presents the evaluation of the GREENNESS solution considering numerical analysis and simulations. Section V draws the main conclusions and points out the future work.

II. RELATED WORK

The solutions related to the GREENNESS objectives can be classified in 4 types: 1) solutions using an out-of-band control channel; 2) solutions implementing a Wi-Fi Power Saving Mode (PSM); 3) solutions using Medium Access Control (MAC) protocols addressing the energy inefficiency and low network capacity problem; 4) routing solutions which are energy-efficient.

There are examples of solutions that reduce power consumption by using an out-of-band control channel. The time synchronised real-time sensor networking platform proposed in [13] uses an Amplitude Modulation (AM) signal to synchronise the network nodes globally; that platform employs a Time-Division Multiple Access (TDMA) scheme where the nodes do sleep except during their transmission time slot. In [14] a solution is proposed in which a radio-triggered circuit is used to switch the environmental sensors between wake-up and sleep modes; when a sensor node is in the sleep mode, all its components are shut down, except the memory, the interrupt handler, and the timer. A radio signal can power-up the radio-triggered circuit and change nodes' state to wake-up mode. This solution employs a multiple-frequency technique by using a radio-triggered ID (RTID) to improve the selectivity of sensors that should be in wake-up mode. The selectivity of the solution is poor because it selects more nodes than needed to transmit information and uses multiple radios and frequencies. A working prototype for a wake-up radio is presented in [15], but it only operates for ranges up to 10 m. The solutions [16], [17], despite being proposed for very different scenarios, are also based on the concept of shutting down or entering in low power state when a sensor or device is in an idle state. In [18] a solution is proposed for a video surveillance scenario using Bluetooth Low Energy (BLE) radios and Pyroelectric Infrared (PIR) motion sensors to activate the streaming from the cameras to a remote PC when motion is detected. Although the proposed solution addresses the same scenario, it relies on motion to activate the streaming and does not solve the low network capacity problem.

IEEE 802.11 standard proposed an amendment [19] which introduced Power Save Mode (PSM) to increase the lifetime of a Wireless Mesh Network. Three modes were introduced: Active, Light Sleep, and Deep Sleep. Some works [20]–[24] are described in [25] which increase the energy efficiency by keeping a node in Deep Sleep mode when it is not involved in a data transmission.

As mentioned above, some of the WVSN problems are caused by the medium access control mechanism employed, so some solutions aim to improve medium access. S-MAC [26] is a contention-based protocol that uses the sleep mode of wireless radios to save energy and outperforms IEEE 802.11 at light traffic case. However, for video transmitting scenarios S-MAC consumes more energy than IEEE 802.11 because of synchronisation overhead it uses. In [27] HTSMAC is proposed, which improves S-MAC and makes the protocol to switch between two operative modes, S-MAC and RIPPLE, the latter being adequate to transmit images. Although the concept is similar to GREENNESS but uses in-band signaling, in our scenario, the cameras are constantly transmitting video, so there is no need to switch between modes. Moreover, Ripple protocol is designed for multi-hop network multimedia applications, and power efficiency is not considered. QEMAC [28] improved the throughput fairness and energy-efficiency of the standard IEEE 802.11e but was not designed for multi-hop networks and nodes are periodically awake when receiving Request to Send (RTS) frames. An interesting mechanism is presented in [29], in which during the idle listening periods, nodes down-clock their Wi-Fi network interface cards, thus reducing the energy consumption. However, this solution requires a hardware modification to the standard Wi-Fi cards and the existing MAC layer protocol.

The energy-efficient routing techniques are also common. In [30], a literature review of Wireless Multimedia Sensor Networks (WMSN) routing protocols is presented where the authors classify them based on different parameters. One of the categories is QoS based routing which is divided into Latency and Multi-constrained routing protocols. Besides, another category named "warm intelligence-based" routing protocol is inspired by the collective behaviour of intelligent biological species. The last category is based on the network structure, and routing protocols are classified as flat, hierarchical and location routing. Routing techniques based on the network structure are the most popular approach found in the literature to address the energy inefficiency problem in sensor networks, and many solutions are proposed specifically in the context of Wi-Fi-based WVSNs. Different strategies are employed. The solutions presented in [31]–[34] use information about the energy levels of the network nodes to make routing decisions that extend the network lifetime. Since these protocols are proposed for networks specialised in video transmission, they also employ different strategies to assure QoS levels and adapt to the high bandwidth requirements, such as multi-path routing and dropping of dispensable frames. There is evidence that adding mobile sensors in WVSNs may improve their performance, including coverage and energy efficiency [35]. Therefore, another major approach followed is the use of a mobile sink. In [36] a solution that aims at prolonging the WVSNs lifetime is proposed, where the mobile sink approach is combined with hierarchical and energy-aware routing.

The previous solutions try to address the energy inefficiency problem using either routing, MAC, or out-of-band signaling, but none of them was developed for video streaming scenarios in multi-hop topologies, nor is capable of turning OFF completely or switching to sleep mode the Wi-Fi radio of the WVS node when it is not transmitting data. Moreover, GREENNESS controls the access to the medium thus improving the throughput performance and fairness when compared with CSMA/CA-based solutions.

III. GREENNESS

GREENNESS is inspired by PACE [12], which already addresses the low network capacity and throughput unfairness problems. PACE consists of a simple multi-hop scheduling mechanism for WVSNs overlaid over the IEEE 802.11 MAC, which limits transmissions to a single WVS at each time and ensures that each node has the opportunity to transmit a packet in each network-wide transmission round; however, it was not designed to be energy efficient. Herein we assume the following: 1) the routing protocol used by GREENNESS configures a logical tree rooted at the gateway, hereafter called the active tree topology; 2) the gateway knows the route to each WVS and each WVS knows the route to the gateway. GREENNESS novelty lies in a centralised node scheduling mechanism that runs in the gateway, together with an LPR integrated into each WVS node. The node scheduling mechanism, using an associated protocol, enables/disables WVS transmissions, and turns the WVS Wi-Fi radios ON/OFF accordingly. The LPR allows establishing an energy-efficient out-of-band control channel between the gateway and the WVS nodes. Fig. 2 illustrates the GREENNESS concept. In what follows, we present the node scheduling mechanism, its companion WVSN active topology collection mechanism, and the requirements for the LPR in each WVS. Table 1 provides the notations used in the description of the WVSN Active Topology Collection and Node Scheduling algorithms.

A. WVSN ACTIVE TOPOLOGY COLLECTION MECHANISM

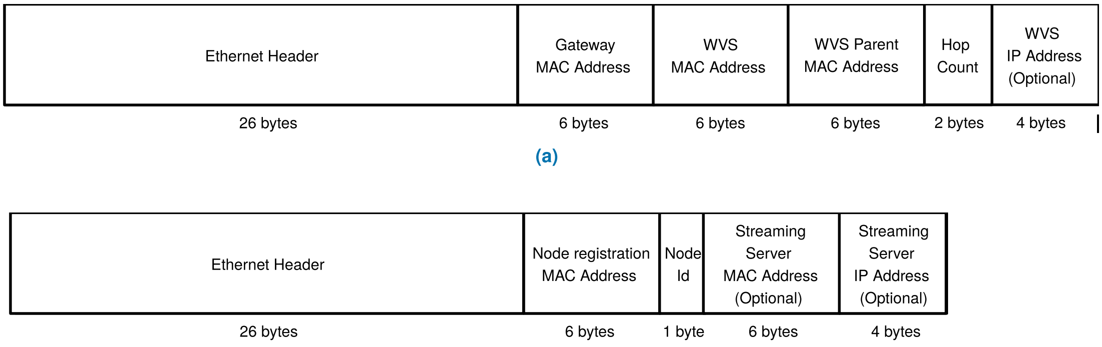
Each WVS registers itself in the gateway by sending a *Registration* message with its MAC address and the MAC address of its parent in the logical tree rooted at the gateway. We assume each WVS learns its parent in the active topology through the routing protocol used, e.g., WiFIX. This set of messages allows the gateway to compute the WVSN active topology. For each new *Registration* message received, the gateway generates a *nodeId*. The *nodeId* is an integer with initial value equal to 1. Each time a new *Registration* message is received at the gateway the *nodeId* is incremented, thus a unique *nodeId* is guaranteed for each WVS. The *nodeId* will be used by the node scheduling mechanism running at the gateway to address each WVS through the LPR. The gateway then sends a *Registration Acknowledgement* message to the source WVS with the *nodeId*. These messages are sent through Wi-Fi. In order to minimize the number of bytes sent through the LPR in the next phases, all nodes in the path between the current WVS and the gateway snoop the message and get the *nodeId*; this way, when the gateway signals a WVS to turn ON its Wi-Fi radio all the nodes in the path will also turn ON their Wi-Fi radio, allowing the message to be relayed all the way up to the gateway. To avoid flooding of Address Resolution Protocol (ARP) messages, the *Registration* message can include the WVS IP address and MAC address; the gateway stores in its ARP table the WVS MAC address and corresponding IP address. For the same reason, the *Registration Acknowledgement* can include the streaming server MAC address; when the *Registration Acknowledgement* message reaches the WVS, it also stores the streaming server MAC address and corresponding IP address in its ARP table. Fig. 3 shows the format of the *Registration* and *Registration Acknowledgement* messages.

TABLE 1. Notations used in the description of the WVSN Active Topology Collection and Node Scheduling algorithms.

Notation	Description
$S[k]$	MAC address of WVS k
$H[k]$	Hop count of WVS k to the gateway
$P_M[k]$	MAC address of the parent of WVS k
$P[k]$	$nodeId$ of the parent of WVS k
l	Branch of the WVSN active topology
N	Number of WVSs in WVSN, including the gateway
D	Depth of the active tree
N_{leaves}	Number of leaf nodes in the active tree
B_l	$nodeIds$ associated to branch l
$T[u]$	Last $nodeId$ parent that was last included in vector B_l and stored in position u
$L[l]$	Last $nodeId$ inserted in vector B_l and stored in position l
h_{maxval}	Highest hop count found in vector H
$V[x]$	$nodeId$ of the x^{th} node to be polled, $x \in \{1, ..., N-1\}$
M_{Poll}	Number of $Poll$ messages sent by the gateway
$M_{warm-up}$	Number of $Poll$ messages used by the algorithm to learn WVS traffic pattern
$T_{GW_{timeout}}$	Gateway polling timeout value
$T_{WVS_{timeout}}$	WVS polling timeout value
$O[i][nodeId]$	Returns 0 or 1 depending on the $nodeId$ and polling interval i, the pattern is stored during the warm-up period using WVS's queue information
$R[s]$	Snooped $nodeId$ in each $Registration$ $Acknowledgement$ message and stored in position s by each relay WVS
$Q[nodeId]$	Queue status for a given WVS with the $nodeId$

The main purpose of the registration mechanism is to let the gateway compute the WVSN active topology and construct the polling vector, which is an ordered list of *nodeIds* that will be used by the node scheduling mechanism. Every time a new *Registration* message arrives at the gateway a set of local vectors are updated.

Vector S contains the MAC addresses of nodes received in the *Registration* messages, $S[k]$ is the MAC address of the node having the *nodeId* k, where $k \in \{1, \ldots, N-1\}$ and N is the number of nodes in the WVSN, including the gateway. In Fig. 2, $N = 7$ and $S[1] = mac_1$. Vector H



(a)

(b)

FIGURE 3. Messages used to collect the WVSN active topology. (a) Registration message. (b) Registration Acknowledgement message.

stores the hop count of each WVS to the gateway, with $H[k]$ representing the hop count of WVS with *nodeId* k (in Fig. 2, $H[3] = 2$). The *Registration* message includes the hop count which is incremented in each WVS. Vector P_M stores the MAC addresses of parents, $P_M[k]$ representing the parent of WVS k (in Fig. 2, $P_M[3] = mac_1$); $P_M[k]$ is an auxiliary vector. After receiving all *Registration* messages, the vector P, representing the parent nodes, is created by searching each $P_M[j]$ in $S[k]$ and making $P[j] = k, j \in \{1, \ldots, N-1\}$ (in Fig. 2, $P[3] = 1$). The first objective of the algorithm is to find the set of WVSs that compose each branch of the active tree topology. For each branch of the tree, the gateway creates the vector B_l which contains the list of *nodeIds* that belong to branch l. B_l includes the *nodeIds* of the WVS nodes that belong to the branch $l \in \{1, \ldots, N_{leaves}\}$, where N_{leaves} is the number of leaf nodes in the active tree topology (in Fig. 2, $N_{leaves} = 4$). $B_l[d]$ is the *nodeId* of the WVS from branch l at position $d, d \in \{1, \ldots, D\}$, where D is the depth of the active tree (in Fig. 2, $D = 2$). The first position of the vector includes the *nodeId* of the leaf node; the other positions include the sequence of WVSs up to the gateway. The algorithm starts by finding in H the maximum elements with hop count, h_{maxval}, i.e., the leaf nodes in the active topology. The tree network topology in Fig. 2 is a balanced binary tree, so all leaves have the same hop count and $h_{maxval} = 2$. Next, all *nodeIds* from H that have a hop count equal to h_{maxval} are added to $B_l[0]$; one B_l vector is created for each *nodeId* found in H. Then, $B_l[1]$ includes the parent *nodeId*, which can be obtained by looking up in the P; this process is repeated for $B_l[2]$, $B_l[3], \ldots, B_l[N_{leaves}]$, and stops when the parent *nodeId* is the gateway. For the network topology in Fig. 2, four vectors are created with the following values: $B_1 = [3, 1]$, $B_2 = [4, 1]$, $B_3 = [5, 2]$, and $B_4 = [6, 2]$. Subsequently, the algorithm has to identify the missing branches with hop count lower than h_{maxval}. It starts by finding the *nodeIds* that have $(h_{maxval} - 1)$ hop count and were not yet added to B_l. If a new branch is found, l is incremented and the first element and its parent (in case the WVS parent is not the gateway) are added to B_l. The new B_l is created using P and the recursive process explained above.

Finally, the vector V can be obtained. Vector V represents the polling order of the WVSs and it can be obtained by concatenating the vectors B_l. The repeated *nodeIds* are removed since different branches can have the same node included in their list. For instance, in Fig. 2, *WVS*#1 is common to leaf nodes *WVS*#3 and *WVS*#4. Vector V is used by the node scheduling mechanism to poll the WVSs (in Fig. 2, $V = [3, 1, 4, 5, 2, 6]$). The WVSN Active Topology Collection Mechanism described above is formally described as a computer algorithm running in the gateway in Algorithm 1.

B. NODE SCHEDULING MECHANISM

The node scheduling mechanism is controlled by the gateway and relies on the topology information provided by the WVSN Active Topology Collection Mechanism. As explained in Section III-A, for each *Registration* message received the gateway generates a new *nodeId* that is used to address the corresponding WVS through the LPR. Algorithm 2 and Algorithm 3 formally define the node scheduling mechanism that runs over the LPR installed in the gateway and in each WVS node, respectively. It works as follows. Initially, each node keeps the Wi-Fi radio switched ON. After successfully registering in the gateway, all WVS nodes switch OFF their Wi-Fi radios. Then, for each element found in vector V, the gateway sends a *Poll* message through the LPR containing the *nodeId* of the WVS that should turn the Wi-Fi radio ON and a bit which is set to 1 when the gateway has data to be transmitted to the WVS. Each WVS verifies whether its *nodeId* is included in the *Poll* message. Next, the WVS whose *nodeId* matches the one included in the *Poll* message checks whether the gateway has data to transmit by checking the bit in the *Poll* message. When the gateway has data to transmit, a timeout $T_{WVS_{Tout}}$ is configured and the WVS waits for a packet from the gateway. After receiving it or $T_{WVS_{Tout}}$ has expired, the WVS can send its own packet to the gateway. During the registration phase of the WVSN Active Topology Collection Mechanism each WVS stores in vector R the *nodeId* that was attributed to a child node by snooping the *RegistrationAcknowledgment* message. Every

Algorithm 1 WVSN Active Topology Collection

```
$R_n \leftarrow$ number of different Registration messages received
$N \leftarrow R_n + 1$
for $k \in [1..R_n]$ do
    $S[k] \leftarrow$ WVS source MAC address
    $H[k] \leftarrow$ hop count
    $P_M[k] \leftarrow$ WVS parent MAC address
end for
for $j \in [1..(N-1)]$ do
    for $i \in [1..(N-1)]$ do
        if $P_M[j] = S[i]$ then
            $P[j] \leftarrow i$
        end if
    end for
end for
$l \leftarrow 0$
$d \leftarrow 0$
$u \leftarrow 0$
$h_{maxval} \leftarrow max(H[k])$
for $k \in [1..sizeof(S[k])]$ do
    if $H[k] = h_{maxval}$ then
        if $d \neq 0$ then
            $l \leftarrow l + 1$
            $d \leftarrow 0$
        end if
        $B_l[d] \leftarrow k$
        $d \leftarrow d + 1$
        $B_l[d] \leftarrow P[k]$
        $T[u] \leftarrow P[k]$
        $L[l] \leftarrow P[k]$
        $u \leftarrow u + 1$
        $d \leftarrow d + 1$
    end if
end for
for $i \in [1..h_{maxval}]$ do
    for $j \in [0..l]$ do
        if $P[L[j]] \neq 0$ then
            $B_j[sizeof(B_j)] \leftarrow P[L[j]]$
            $L[j] \leftarrow P[L[j]]$
            if $L[j] \notin T[u]$ then
                $T[u] \leftarrow P[L[j]]$
                $u \leftarrow u + 1$
            end if
        end if
    end for
    for all $k \in [1..sizeof(S[k])]$ do
        if $H[k] = (h_{maxval} - i)$ and $k \notin T$ then
            $l \leftarrow l + 1$
            $d \leftarrow 0$
            $B_l[d] \leftarrow k$
            if $P[k] \neq 0$ then
                $d \leftarrow d + 1$
                $B_l[d] \leftarrow P[k]$
                $L[l] \leftarrow P[k]$
                if $L[l] \notin T$ then
                    $T[u] \leftarrow L[l]$
                    $u \leftarrow u + 1$
                end if
            end if
        end if
    end for
end for
$x \leftarrow 0$
for $j \in [0..l]$ do
    for $i \in [0..sizeof(B_j)]$ do
        if $B_j[i] \notin V$ then
            $V[x] \leftarrow B_j[i]$
            $x \leftarrow x + 1$
        end if
    end for
end for
```

Algorithm 2 Node Scheduling Algorithm Running in the WVSN Gateway

```
$i \leftarrow 0$
$M_{Poll} \leftarrow 0$
while True do
    Increment $M_{Poll}$
    for all $nodeId \in V$ do
        if $M_{Poll} =< M_{warm-up}$ then
            send Poll message with nodeId
            if hasData=True then
                send packet to WVS
            end if
            set $T_{GW_{timeout}}$
            while packet from nodeId not received OR $T_{GW_{Tout}} > 0$ do
                if packet from nodeId is received then
                    set $Q[nodeId]$
                end if
                Decrement $T_{GW_{Tout}}$
            end while
        end if
        if $T_{GW_{timeout}} < 0$ OR $Q[nodeId] = 0$ then
            $O[M_{Poll}][nodeId] \leftarrow 0$
        else
            $O[M_{Poll}][nodeId] \leftarrow 1$
        end if
        if $M_{Poll} > M_{warm-up}$ then
            if $O[i][nodeId] = 1$ OR $Q[nodeId] => 1$ then
                send Poll message with nodeId
                if hasData=True then
                    send packet to WVS
                end if
                set $T_{GW_{Tout}}$
                while packet from nodeId not received OR $T_{GW_{Tout}} > 0$ do
                    Decrement $T_{GW_{Tout}}$
                end while
            end if
            $i \leftarrow i + 1$
            if $i => Warm-up$ then
                $i \leftarrow 0$
            end if
        end if
    end for
end while
```

relay WVS that finds its *nodeId* in *R* switches its Wi-Fi radio ON. In the gateway, a timeout $T_{GW_{Tout}}$ is configured to assure that in case of failure another WVS is scheduled to transmit. The gateway checks if data from *nodeId* has been received or $T_{GW_{Tout}}$ has expired; while these conditions are not met $T_{GW_{Tout}}$ is decremented. If a packet from *nodeId* is received or $T_{GW_{Tout}}$ expires, the gateway polls the next element in *V*. When the WVSs do not find their *nodeId* in the *Poll* message or in *R*, the Wi-Fi radio is switched OFF. This algorithm is repeated until all *nodeIds* have been polled by

Algorithm 3 Node Scheduling Algorithm Running in the WVS Upon Receiving *Poll* Message

```
for all Poll messages received do
    Increment $M_{Poll}$
    if $nodeId = myNodeId$ then
        turn Wi-Fi radio ON
        if hasData=True then
            set $T_{WVS_{Tout}}$
            while packet from gateway not received OR $T_{WVS_{Tout}} > 0$ do
                Decrement $T_{WVS_{Tout}}$
            end while
        end if
        if $M_{Poll} <= M_{warm-up}$ then
            if data available then
                send packet and include queue size
            else
                send a packet with queue size
            end if
        else
            while New Poll message is not received do
                if data available then
                    send packet and include queue size
                end if
            end while
        end if
    else
        turn Wi-Fi radio OFF
    end if
    if $nodeId \in R$ then
        turn Wi-Fi radio ON and forward packets
    end if
end for
```

the gateway and the polling cycle has been completed. After that, the first node is scheduled again, and a new polling cycle is initiated.

In a video monitoring scenario, the WVS bit rate will depend on the camera video quality and resolution. So, for low video quality, the WVS duty cycle would be short. This may mean that a WVS receiving a *Poll* message may not have packets to transmit to the cloud server. To further improve energy-efficiency, the node scheduling mechanism is designed to be traffic-aware. During the period of time the gateway knows there will be no traffic from a given WVS, the WVS is not polled and the Wi-Fi radio is kept OFF.

In Algorithm 2, after a warm-up period, the gateway will only send a *Poll* message according to the WVS traffic pattern. During the first set of *Poll* messages, $M_{warm-up}$, Algorithm 2 stores in $O[\ ][\ ]$, for each *nodeId* and *Poll messageId*, the current queue status (0 - empty; 1 - otherwise); even if the WVS does not have a packet to transmit, a packet with this information is sent to the gateway. During the warm-up period, $M_{warm-up}$, the gateway stores 1 or 0 in $O[messageId][nodeId]$ according to the queue status received from each *nodeId*. After the warm-up period, $M_{warm-up}$, the gateway will replay the traffic pattern initially learned for each *nodeId*. The WVSs will no longer be forced to send a packet, but the queue status is still included in the packets sent to the gateway. For Constant Bit Rate (CBR) video streams this estimation can be easily performed and enables further energy savings.

C. LOW POWER RADIO TECHNOLOGIES CANDIDATES

In GREENNESS, LPRs play an important role not only for reducing the energy consumption of the WVSN but also to control the access to the medium. The LPR technology needs to fulfil the following set of requirements:

1) the radio coverage shall be large enough to enable communications between the gateway and each WVS forming the Wi-Fi-based multi-hop network;
2) the power consumption shall be lower than the power consumption of a Wi-Fi radio in idle mode;
3) the payload length should be at least 9 bit (8 bit for the *nodeId* and 1 bit to indicate whether the gateway has traffic to be delivered);
4) the inter-frame interval should be similar to the one achieved by the control in-band using Wi-Fi in [12] to assure the same performance results;
5) unidirectional communications between the gateway and each WVS shall be guaranteed – bidirectionality is optional.

Taking into account these requirements, we have identified the set of candidate LPRs shown in Table 2; this list is not exhaustive, and other LPRs may fulfil the GREENNESS requirements as well. FM-RDS [37] has been initially considered in [8], motivated by its high radio range (from 50 m to 100 km), and low power consumption (49.2 mW). Although an RDS group of 104 bit will be enough to carry the *nodeId* and 1 bit to indicate whether the gateway has traffic to be delivered, there is a limitation related to the use of the RDS control channel to run the GREENNESS node scheduling mechanism. The standard states that the RDS bitrate must be precisely $1,187.5\ bit/s \pm 0.125\ bit/s$ [37]. Since the standard also specifies RDS groups of 104 bit and the transceivers require the generation of an entire RDS group, it takes $\frac{104\ bit}{1187.5\ bit/s} \approx 87.58\ ms$ to send a polling request. This results in a packet rate of ≈ 11.4 packets/s, which increases the jitter and delay of the video transmission. The jitter and delay are affected because the GREENNESS node scheduling mechanism will need more time to poll each WVS. Moreover, FM-RDS only allows unidirectional connections and relies on message redundancy to recover from errors.

IEEE 802.15.4 radios using the 868/915/2450 MHz bands are an alternative. The Atmel AT86RF212 transceivers, for example, are optimized for low power communications and support up to 250 kbit/s. Although the radio range of IEEE 802.15.4 is similar to the radio range of IEEE 802.11, IEEE 802.15.4 supports mesh topologies. When the transceiver is

TABLE 2. Candidate low power radios.

Standard	Max. Range	Power consumption	Max. Payload Length	Min. Inter-frame Interval
FM-RDS	100 km	49.17 mW	104 bit	87.58 ms
802.15.4	100 m	30.36 mW	127 B	1.06 ms
802.15.4g	1 km	57 mW	2,047 B	0.21 ms
BLE	100 m	44.22 mW	27 B	7.5 ms

ON, the power consumption is only 30.36 mW [38]. The minimum inter-frame interval is 1 ms, similar to the one achieved in [12] with Wi-Fi. Moreover, IEEE 802.15.4 allows bidirectional communications, which can enable the implementation of recovery mechanisms when a polling message is not received, for example.

The IEEE 802.15.4g standard was defined by the Smart Utility Networks (SUN) Task Group as an amendment to IEEE 802.15.4 to enable the deployment of very large scale process control applications, such as the utility smart grid network capable of supporting large, geographically dispersed networks with minimal infrastructure. The transceiver CC1200 from Texas Instruments, for example, has a radio range up to 1 km, enabling scenarios of sparse WVS nodes across a large geographic area. This transceiver can operate at 1,250 kbit/s with a typical power consumption of 57 mW for receiving data in low-power mode [39]. As in IEEE 802.15.4, the minimum inter-frame interval meets the requirements and also allows bidirectional communications.

BLE – operating in the 2.4 GHz frequency band is another candidate LPR. BLE has radio range lower than Wi-Fi, but the standard includes mesh networking capabilities. The nRF51822, for example, is a System-on-Chip that implements BLE. The maximum power consumption is 44.22 mW [38]. BLE also supports bidirectional communications.

In conclusion, there are several candidate LPR technologies. FM-RDS was already demonstrated and tested in [9], which allowed us to prove that it could be used despite the long inter-frame interval imposed. The radio coverage of FM-RDS also imposes restrictions since the 100 km range is only possible for licensed broadcasters; for unlicensed broadcasters, a range of 50 m can be achieved using the so-called Low Power FM. We believe the use of IEEE 802.15.4 or IEEE 802.15.4g can bring advantages such as higher range (for IEEE 802.15.4g, 1 km range) and bidirectional communications, allowing the implementation of recovery mechanisms for control messages or more advanced scheduling mechanisms. These new scheduling mechanisms enable the possibility of WVSs to request access to the medium and change the polling order. Moreover, by having a higher bit rate and a lower inter-frame interval (lower than 1.06 ms), we can improve the overall latency of the network because the *Poll* of each WVS can be performed faster. LoRaWAN is an example of the most adopted Low-Power Wide Area Networking (LPWAN) and could be thought as a candidate LPR too. However, with a duty-cycle of 1 %, it is not suitable. This is because the inter-frame interval is too high, disabling real-time control of the Wi-Fi radios. In the future, we may consider IEEE 802.11ah (Wi-Fi HaLow), since this new standard promises higher ranges and lower power consumptions, while keeping a low inter-frame interval. It was not included herein because the chipsets will only become available in 2018.

IV. GREENNESS EVALUATION

GREENNESS was evaluated using numerical analysis and simulations. This section first presents the evaluation methodology. Then, we analyse the energy consumption of a WVSN for GREENNESS numerically and compare it with the state of the art solution. Finally, we describe the ns-3 simulations carried out also considering traffic aspects.

A. EVALUATION METHODOLOGY

The evaluation methodology was designed to verify whether, in fact, GREENNESS can save energy while improving throughput and fairness, by comparing it to state of the art CSMA/CA-based WVSN solutions. To achieve this objective we have proceeded as follows: 1) estimated the GREENNESS and PACE energy consumption for random network topologies numerically; 2) assessed by means of ns-3 simulations the energy saving for random network topologies and compared it with numerical results for validating the numerical analysis; 3) characterised the impact of different LPR power consumption and the switching of Wi-Fi radios to sleep mode on GREENNESS energy savings; and 4) used simulations to study the energy savings for different offered traffic loads and compared performance of GREENNESS against CSMA/CA-based WVSN solutions.

The numerical estimation of GREENNESS and PACE energy consumption for random network topologies was performed to easily evaluate, for different scenarios, the energy saving attained without running a simulation. GREENNESS and PACE energy consumption numerical analysis was first studied in [8] for regular topologies, and it is extended in this article for random topologies. Although PACE was not designed to be energy efficient, by controlling the access to the medium, it avoids packet collisions and is indeed more efficient than CSMA/CA-based WVSN solutions, as shown in [12]. Using this analysis, the energy savings were estimated for a scenario where one packet is transmitted from every single WVS to the gateway.

GREENNESS was implemented in the network simulator 3 (ns-3) in order to analyse the energy savings that could be attained and to compare them with the numerical results. Moreover, the implementation in ns-3 allowed us to study the performance regarding throughput fairness. The simulations were performed with 8,874 random wireless multi-hop networks with 10, 20, and 30 WVSs. The 8,874 WVSNs were used to analyse the energy consumption for 12 different average number of hops (2 until 4.2), assuring at least

50 simulations for each. Afterwards, an analysis of ns-3 simulation results was performed and the numerical analysis validated.

The numerical analysis was used to study the impact of LPR power consumption in the energy saving of GREENNESS. This analysis assesses energy saving achieved by GREENNESS in case we select one of the candidate LPRs. Moreover, we evaluated the scenario when Wi-Fi radios are not switched OFF since in practice this can cause energy transient effects or delays as the WVSs need to re-associate to a neighbour WVS. Instead, the Wi-Fi radios of WVSs were considered to be switched to sleep mode and so the Wi-Fi sleep power consumption was also considered in the numerical analysis and its impact on GREENNESS energy savings.

The energy efficiency of the traffic-aware feature of the Node Scheduling Mechanism was also evaluated for different offered network loads using ns-3 simulations. Afterwards, GREENNESS performance assessment was performed against CSMA/CA-based WVSN solutions. Using the same WVSN topologies, the throughput and Jain's Index, which measures the level of fairness, were compared between GREENNESS and CSMA/CA for different offered network loads.

B. NUMERICAL ANALYSIS

We assume a scenario in which all WVSs transmit data to the gateway. The total energy E spent by the network considering the transmission of a successful frame from each WVS to the gateway can be defined as follows [40]:

$$E = E_{tx} + E_{rx} + E_{idle} + E_{overhear} \tag{1}$$

where E_{tx} and E_{rx} are respectively the total energy required to transmit the frame and the total energy required to receive one frame from all WVSs, E_{idle} is the total energy that all WVSs spend in idle mode, and $E_{overhear}$ is the total energy spent by all WVSs when receiving packets that are destined to other nodes. GREENNESS aims at minimizing E_{idle} and $E_{overhear}$ by switching OFF the Wi-Fi radio.

As it can be observed from (1) the total energy consumption depends on the energy consumption of the transceiver when it is either transmitting, receiving, or in idle mode. Wi-Fi idle listening and receiving are the dominant modes of energy consumption under light and moderate traffic conditions [40], [41]. P_{tx} and P_{rx} are calculated by adding to P_{idle} a value that is hundred times smaller, which means that P_{tx}, P_{rx}, and P_{idle} are approximately equal [42]. This implies that the energy consumption of the network is mainly dependent on the time that each node spends in one of the three Wi-Fi modes mentioned. Simplifying (1) we get:

$$E = P_{idle} \cdot T_{total} \tag{2}$$

From (2) we can verify that the energy consumed by the network depends on the total time T_{total} spent by all WVSs in transmitting or receiving information, in idle mode waiting for information, or in overhearing packets. Thus, our analysis is focused on the amount of time WVSs spend in each mode. Given the power consumption P_{idle} is provided by the manufacturer of the Wi-Fi radio and the LPR, we simply have to estimate the interval of time T_{total} for which the WVSs have their Wi-Fi radio ON. The total time required for a given WVS in a WVSN with N nodes, including the gateway, to transmit one packet to the gateway when using PACE is defined in (3). PACE implements a polling mechanism and is herein assumed as the reference state of the art approach since it outperforms CSMA/CA in multi-hop scenarios [12].

$$t_{PACE} = \sum_{i=1}^{N_{leaves}} \frac{h_i \cdot (h_i + 1)}{2} N \cdot T - F_{cor} \cdot T \tag{3}$$

$$F_{cor} = \sum_{i=1}^{N-1} h_i \cdot \Big(\sum_{j=1}^{N_{leaves}} x_{ij} - 1 \Big) \tag{4}$$

$$x_{ij} = \begin{cases} 1 & \implies i \in B_j \\ 0 & \implies i \notin B_j \end{cases} \tag{5}$$

In (3), h_i is the number of hops for branch i, N_{leaves} is the number of branches of the tree defining the WVSN active topology, N is the number of WVSs including the gateway, T is the time for a WVS to transmit a frame and receive the corresponding acknowledgement from its parent and F_{cor} is a correction factor to cancel the transmission time of each relay WVS. If IEEE 802.11e Enhanced Distributed Channel Access (EDCA) is used, the frames with QosNoAck are not acknowledged. In that case, T would simply be the time for a WVS to transmit a frame, thus saving the time required for the acknowledgements and possible retransmissions. Herein, we assumed the worst-case scenario where all frames are acknowledged. F_{cor} varies with the WVSN topology and is given by (4) and (5), which count the number of times a WVS node is included in vector B_j, where $j \in \{1, \ldots, N_{leaves}\}$. A simple example can be given using Fig. 2. *WVS*#1 is included in the branches of *WVS*#3 and *WVS*#4, and *WVS*#2 is included in the branches of *WVS*#5 and *WVS*#6. For this example, F_{cor} equals 2, i.e., the number of repeated WVSs for the aforementioned branches.

Equation (6) defines the total time required for all WVSs to transmit one packet to the gateway when GREENNESS is considered. F_{cor} can be calculated using (4) and (5).

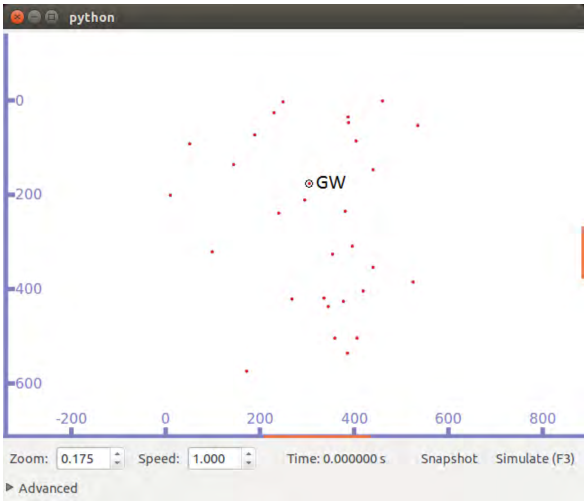
$$t_{GREENNESS} = \sum_{i=1}^{N_{leaves}} \frac{h_i \cdot (h_i + 1) \cdot (h_i + 2)}{3} \cdot T - F_{cor} \cdot T \tag{6}$$

The total energy consumed by all the WVSs in the network can be calculated by using (7) and (8):

$$E_{PACE} = P_{idle} \cdot t_{PACE} \tag{7}$$

$$\begin{aligned} E_{GREENNESS} = {} & P_{idle} \cdot t_{GREENNESS} + P_{LPR} \cdot t_{LPR} \\ & + P_{WiFi_{sleep}} \cdot t_{WiFi_{sleep}} \end{aligned} \tag{8}$$

In (8) P_{LPR} is the power consumption of the LPR, t_{LPR} is the time all LPRs in the WVSs are active, $t_{WiFi_{sleep}}$ is the time



Zoom: 0.175 Speed: 1.000 Time: 0.000000 s

FIGURE 4. **Network simulation with 30 WVSs randomly positioned in a 500 m × 500 m area with the gateway on the top centre position.**

Wi-Fi radios in the WVSs are in sleep mode and $P_{WiFi_{sleep}}$ is the power consumption of a Wi-Fi radio in sleep mode. With the inclusion of the $P_{WiFi_{sleep}}$ and $t_{WiFi_{sleep}}$ we are considering the case where it is not possible to switch OFF the Wi-Fi radio, and we switch it to sleep mode.

The energy saving enabled by GREENNESS can then be calculated using (9):

$$E_{saving} = \left(1 - \frac{E_{GREENNESS}}{E_{PACE}}\right) \times 100\,(\%) \tag{9}$$

C. SIMULATION SETUP

The implementation of GREENNESS in ns-3 (version 3.24.1) required three steps: 1) implementation of the WVSN active topology collection mechanism, which is used to calculate the polling vector; 2) implementation of the node scheduling mechanism; 3) generation of 14 thousand random wireless multi-hop network topologies with 10, 20, and 30 WVSs. Algorithm 1 was used to build the node scheduling vector. From the 14 thousand random wireless multi-hop networks 8,874 where in fact used, as only for these topologies all the WVSs from the WVSN could reach the gateway, either directly or through a relay WVS. Furthermore, we needed to simulate this amount of WVSN topologies in order to guarantee at least 60 active tree topologies rooted at the gateway for each of the 12 different tree depths simulated. An example of a network with 30 nodes randomly positioned in a 500 m per 500 m space is illustrated in Fig. 4. MAC and IP addresses were added to the ARP cache table of each node in order to avoid ARP requests during the registration phase. The simulation parameters used are summarized in Table 3. The power values for each technology are shown in Table 4. For the low power radio, we used as reference the CC1200 transceiver that implements 802.15.4g with a maximum power consumption of 57 mW. The Intel Wi-Fi, Link 5300 a/b/g/n wireless network adapter was selected, which has a power consumption of 1.45 W in idle mode and 100 mW in sleep mode [43]. The energy results for GREENNESS and PACE were obtained by using the ns-3 energy models. For the simulation, the traffic load was emulated as a raw H.264 video stream, transmitted at a constant bit rate. The length of each packet was 1280 bytes, including 1200 bytes payload, 28 bytes IP and UDP header and 52 bytes MAC. The transmission bit rate of each WVS was increased in steps of 50 kbps to increase the offered load.

TABLE 3. **Simulation parameters.**

Simulation Variable	Value
No. of runs per test	30
Area where nodes are placed	500 m x 500 m
$RxGain$	5 dB
TxPowerStart	16 dB
TxPowerEnd	16 dB
Fragmentation	Disabled
Packet payload Size	1,200 bytes
RTS/CTS	Disabled
Mobility model	None
Propagation Loss model	Friis Propagation Model
Propagation Delay model	Constant Speed Model
Communications standard	IEEE 802.11b
Data Rate	11 Mbps

TABLE 4. **Values of the parameters P_{LPR}, P_{idle}, and $P_{WiFi_{sleep}}$ considered in the numerical and simulations analysis.**

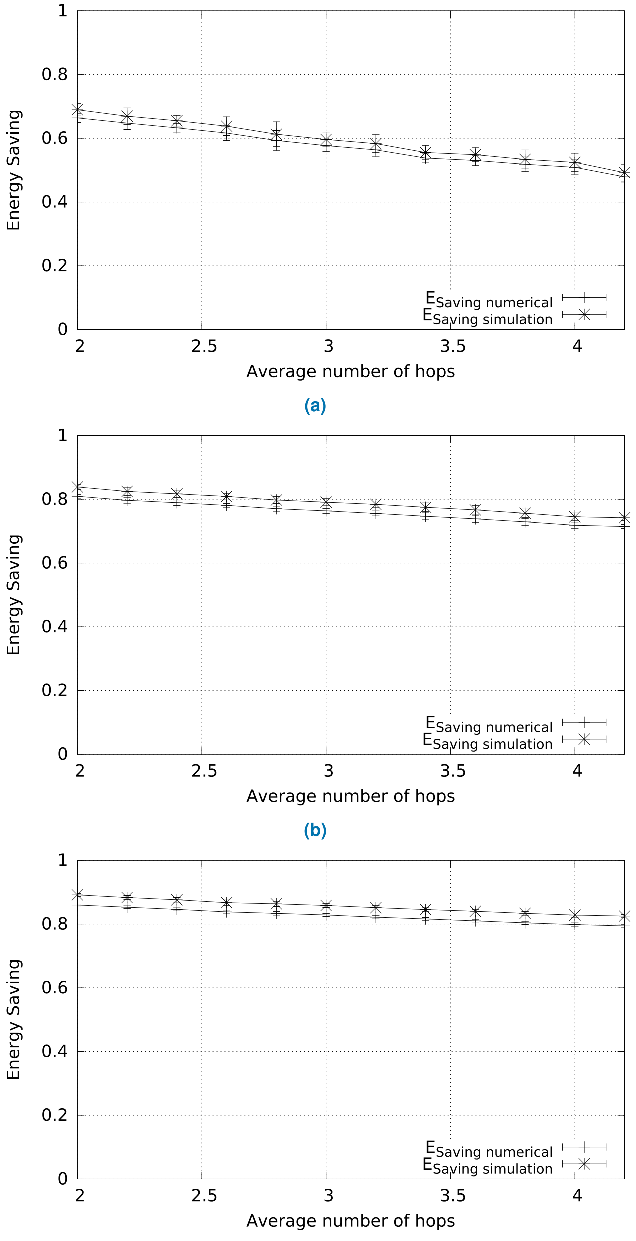
Constant	Value
P_{LPR}	57 mW
P_{idle}	1.45 W
$P_{WiFi_{sleep}}$	100 mW

For the numerical analysis, the values of T, t_{LPR}, N_{leaves}, F_{cor} and h_i in (3) and (6) were obtained from simulation for each random multi-hop topology. Besides, the average number of hops was calculated for each multi-hop topology by averaging the depth of each branch of the active tree topology rooted at the gateway.

D. EVALUATION RESULTS

The evaluation of GREENNESS and PACE is presented in this section. Fig. 5 shows the energy saving for WVSNs with 10, 20, and 30 nodes calculated using (9). For each topology, the average hop count and the energy saving is computed. The simulation results prove that (7) and (8) are correct.

The plots in Fig. 5 show that the numerical and simulation curves are coincident for a confidence interval of 95 %, thus validating our numerical analysis. For $N = 10$, the energy saving ranges between 45 % and 65 %, while for $N = 30$ it ranges between 79 % and 85 %. So, the energy saving increases as the network size increases. When the average number of hops rises, the energy saving decreases since WVSs need more time to transmit a packet to the gateway as it is relayed by more WVSs. Nevertheless, for bigger network sizes, the gradient of the energy saving curve is almost zero.

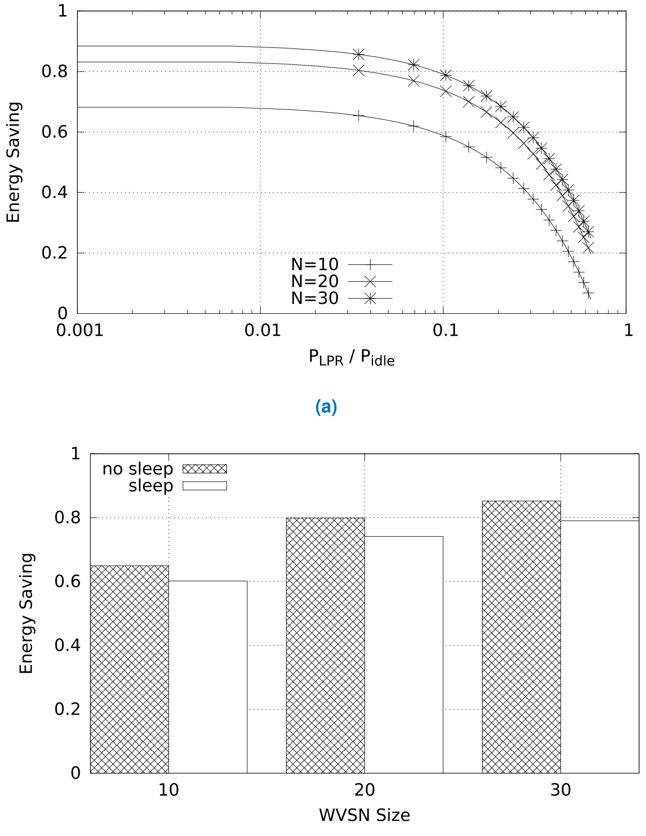


(a)

(b)

(c)

FIGURE 5. **Energy saving achieved by GREENNESS with respect to PACE for WVSNs with different sizes and average number of hops. (a) $N = 10$. (b) $N = 20$. (c) $N = 30$.**



(a)

(b)

FIGURE 6. **Energy saving exhibited by GREENNESS when varying P_{LPR} and considering Wi-Fi radios in sleep mode. (a) Energy saving achieved by GREENNESS with respect to PACE when P_{LPR} is varied. (b) Energy saving achieved by GREENNESS when considering Wi-Fi radios are put in sleep mode instead of switched OFF.**

This happens because the number of WVSs that are switched OFF tends to be higher than the number of WVSs switched ON in a given moment.

In order to analyse the way the energy saving achieved by GREENNESS changes with P_{LPR}, we have performed a sensitivity analysis using (7), (8), and (9). From the curves presented in Fig. 6(a), we can conclude that the energy saving is almost constant for LPRs consuming less than 10 % of P_{idle}. Since the candidate LPRs power consumption is below 4 % of P_{idle}, the energy saving achieved for all the candidate LPRs is similar. When designing the network, the user needs to perform a trade-off between network coverage, which means selecting a radio with higher energy consumption to achieve greater distances and energy saving.

For the case when WVSs Wi-Fi radio is switched to sleep mode instead of switched OFF, from Fig. 6(b) we can conclude that for $N = 30$, the energy saving slightly reduces from 85 % to 79 %. The other WVSNs sizes also suffer a similar reduction in the energy saving. Even when it is not possible to switch OFF the Wi-Fi radio of the WVSs, GREENNESS can achieve significant energy savings. This was expected since $P_{WiFi_{sleep}}$ represents 7 % of P_{idle} and thus the impact in the energy saving is negligible.

The results in Fig. 7 show that GREENNESS can achieve energy saving up to 92 % for random topologies with 10, 20, and 30 nodes. For low offered loads, since the WVSs do not need to transmit data so often, Wi-Fi radios can be switched OFF more time, thus saving more energy. For offered loads higher than 3 Mbit/s, the energy saving is constant, being equal to 85 % for $N = 30$. For bigger WVSNs sizes, the gradient of energy saving curve is small because, as in Fig. 5, the number of WVSs that are switched OFF tends to be higher than the number of WVSs switched ON in a given moment. For smaller WVSNs (e.g., $N = 10$), the traffic-aware mechanism causes an increase of 20 % in the energy saving for

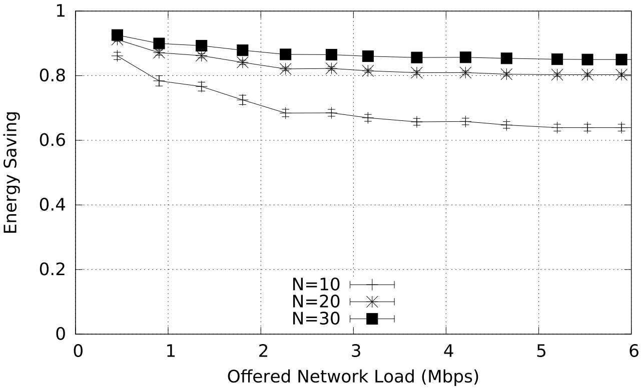


FIGURE 7. **Impact of different offered network loads and WVSNs sizes in the energy saving of GREENNESS.**

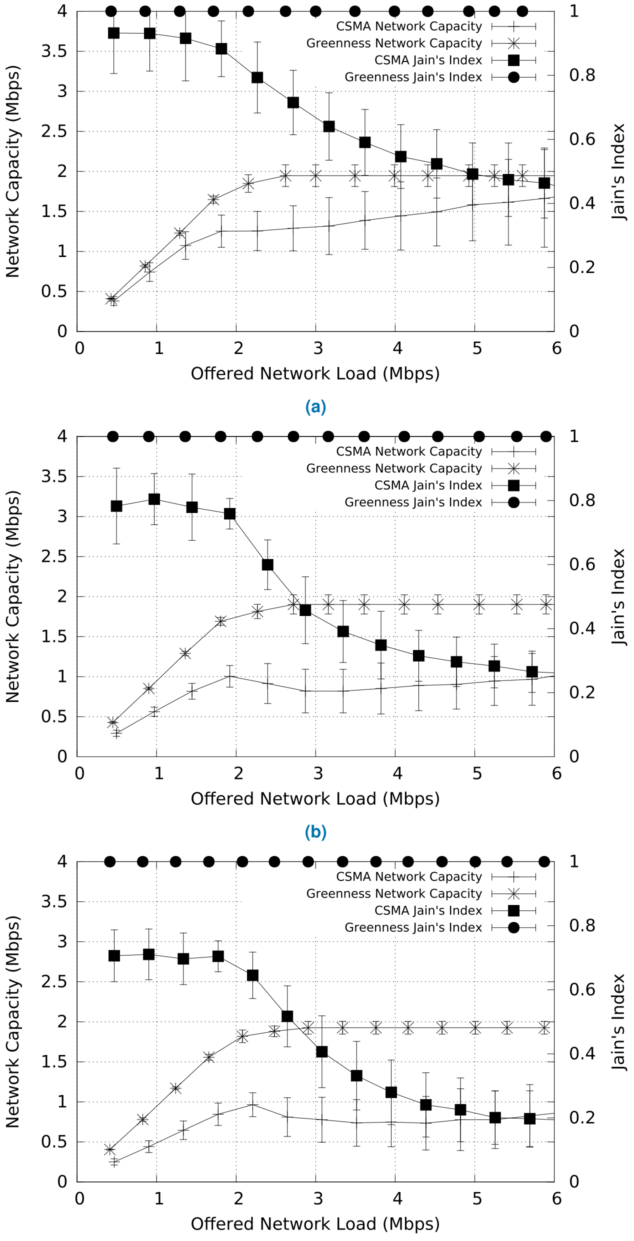
low offered loads. As explained before, the node scheduling mechanism does not send a *Poll* message when the WVS does not have data to be sent. Otherwise, the node scheduling mechanism running in the gateway waits for a timeout $T_{GW_{Tout}}$ to send a new *Poll* message. By not having to wait $T_{GW_{Tout}}$ for small WVSNs sizes, GREENNESS increases the energy saving.

Fig. 8 presents the overall performance achieved by GREENNESS and a CSMA/CA-based solution. As expected, GREENNESS network throughput is constant when saturation is reached; also, the saturation point is reached for offered loads greater than those obtained when CSMA/CA is used. Since in GREENNESS each node has a time slot to transmit information, the Jain's index, which measures the level of fairness, is constant. CSMA/CA fairness decreases when network throughput capacity reaches the limit, meaning that nodes closer to the gateway will have more access to the medium than the others.

GREENNESS not only can achieve energy saving up to 92 % for low offered network loads but it also maintains the same level of performance and fairness for higher offered network loads.

E. DISCUSSION

GREENNESS energy saving increases as the network size increases. Yet, for WVSNs with more than 20 nodes, energy saving is kept almost constant, independently of the variation of the average number of hops, number of nodes, and offered load. Moreover, the impact of the LPR power consumption in GREENNESS energy saving is approximately constant for LPRs consuming less than 10 % of P_{idle}. This means that GREENNESS attains the same energy saving for all candidate LPRs identified in this paper. By switching the Wi-Fi radio to sleep mode instead of switching it OFF does not affect GREENNESS energy saving significantly since $P_{WiFi_{sleep}}$ only represents 7 % of P_{idle}. The node scheduling mechanism was designed to be traffic-aware, but from our evaluation for WVSNs with sizes above 20 nodes the energy saving gain is negligible, thus the algorithm complexity can be reduced for these scenarios. For lower WVSN sizes and low offered loads, the traffic-aware feature can save up to 20 %. Moreover, GREENNESS improves network capacity and throughput fairness when compared to state of the art CSMA/CA-based WVSN solutions. GREENNESS focuses on the link and network layers. If a cross-layer approach is employed, for instance, considering video compression or source coding, the amount of information transmitted would diminish, especially in a multi-hop network where a video stream is transmitted and received by several nodes before reaching the sink, thus the energy gains can be even higher.



(a)

(b)

(c)

FIGURE 8. **Performance of GREENNESS and CSMA/CA for different offered network loads with average number of hops equal to 2. (a) $N = 10$. (b) $N = 20$. (c) $N = 30$.**

Our study could be improved in five main directions: 1) study the solution for different LPR inter-frame intervals;

2) evaluate the performance of WVSNs with average hop count higher than two; 3) study the delay metric; 4) study the WVSN for sizes higher than 30 nodes; and 5) evaluate the solution when using the IEEE 802.11ac standard. We expect that longer LPR inter-frame intervals will increase the video delay and jitter. Preliminary results we have obtained for network topologies having high average hop count showed that the GREENNESS gains would still exist. The delay was not studied, but since GREENNESS algorithm is inspired in PACE, we can consider the values obtained in [12] and conclude that, for non-saturated WVSNs, the traditional CSMA/CA mechanism may have better performance than GREENNESS. The WVSN size was limited to 30 nodes in the evaluation because we consider it to be a reasonable size for a WVSN; moreover, GREENNESS divides the channel capacity by the number of nodes, meaning that above 30 nodes the bit rate for video will be low. In our simulation scenario for $N = 30$ each WVS only obtains 100 kbit/s. In the simulations we adopted the communications standard IEEE 802.11b and Friis propagation model since IEEE 802.11ac for multi-hop CSMA/CA networks and high bit rates was not functioning properly in ns-3 by the time we made the study. Nevertheless, in the numerical analysis, we can observe that the communications standard only affects T, the time for a WVS to transmit a frame and receive the corresponding acknowledgement from its parent. As such, from (9) we can conclude that the GREENNESS energy saving is independent of T.

GREENNESS has a set of important features, including the following: 1) it was designed for multiple traffic scenarios, namely video streaming; 2) incorporates failure detection mechanisms to overcome the loss of LPR messages; and 3) supports high inter-frame interval, which enables the usage of FM-RDS, IEEE 802.15.4, and BLE. Although GREENNESS was evaluated for a scenario where each WVS sends a video stream to a server located in the cloud, it is designed to support traffic from the gateway to the WVSs, for instance, to enable the Real-Time Transport Protocol Control Protocol (RTCP) typically used to control RTP sessions; in each LPR control message we have included a flag that indicates that the gateway has data to be transmitted. When the flag is true, the WVS will first wait to receive data from the gateway. The Node Scheduling Mechanism has built-in failure detection methods to overcome losses of control messages sent over the LPR and failures in the transmission of data packets over Wi-Fi. By configuring timeouts in both the gateway and the WVSs, the algorithm will recover from these failures. The Node Scheduling Mechanism was designed to allow higher inter-frame intervals, which can potentiate the adoption of other LPRs such as IEEE 802.15.4 and BLE that support multi-hop topologies to extend their coverage and achieve the same range as Wi-Fi. LPR candidates should have inter-frame intervals at least equal to the one achieved by the control in-band using Wi-Fi [12]. In fact, this was a simplification since in [12] the control channel used Wi-Fi, and good results regarding network capacity and fairness were attained. We believe that IEEE 802.15.4 and BLE LPRs can also achieve the same results as in [9] since for a WVSN with an average hop count of four this will mean an inter-frame interval of 28 ms, which is much less than the one for FM-RDS.

The GREENNESS solution has two limitations: 1) it needs the installation of an additional radio in each WVS, and 2) the traffic-aware node scheduling mechanism only supports CBR traffic. Although GREENNESS requires the installation of an additional radio, its cost is low and negligible when compared to the rest of the WVS cost [9]. The traffic-aware node scheduling mechanism was designed for CBR traffic and has to be enhanced using WVS queue's size information to support Variable Bit Rate (VBR) traffic.

In conclusion, GREENNESS can offer high energy savings for multi-hop WVSNs and improve network capacity and throughput fairness when compared to state of the art CSMA/CA-based WVSN solutions. Moreover, it incorporates a failure recovery mechanism and a traffic-aware algorithm that enables substantial energy savings, namely for low size WVSNs with low offered loads. The impact on the energy saving for not switching OFF the Wi-Fi radios but only changing them to sleep mode can be neglected and may simplify implementation.

V. CONCLUSIONS

WVSNs are being applied in multiple scenarios ranging from healthcare to surveillance. This is motivated by the high availability of low cost networked wireless devices and video cameras. However, multi-hop IEEE 802.11-based WVSNs suffer from three problems: low network capacity, throughput unfairness, and energy inefficiency. In this paper, we presented GREENNESS and its companion algorithms and mechanisms used to bootstrap a WVSN, collect network topology information, and schedule transmissions. We demonstrated that GREENNESS can achieve energy savings up to 92 % while improving network capacity and fairness compared to CSMA/CA-based WVSNs. For the control channel, it is important to select a low power technology that fulfils the listed requirements. A few candidate LPRs were identified; when designing the network, the LPR can be chosen based on a compromise between radio coverage and energy consumption.

As future work, we will consider the adoption of bidirectional LPRs, which will enable faster recovery mechanisms and improved node scheduling mechanisms, as well as frame aggregation in relay nodes and spatial reuse for further improving WVSN performance and energy-efficiency. We also expect to enhance the traffic-aware mechanism to support Variable Bit Rate (VBR) traffic and to take advantage of the WVS queue's size information.

REFERENCES

[1] H. Bauer, M. Patel, and J. Vieira. (2014). *The Internet of Things: Sizing up the Opportunity*. [Online]. Available: https://www.mckinsey.com/industries/semiconductors/our-insights/the-internet-of-things-sizing-up-the-opportunity

[2] A. Seema and M. Reisslein, "Towards efficient wireless video sensor networks: A survey of existing node architectures and proposal for a flexi-WVSNP design," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 3, pp. 462–486, 3rd Quart., 2011.

[3] F. Al-Turjman, "Cognitive routing protocol for disaster-inspired Internet of Things," *Future Generat. Comput. Syst.*, pp. 1–13, Mar. 2017.

[4] G. Singh and F. M. Al-Turjman, "Learning data delivery paths in QoI-aware information-centric sensor networks," *IEEE Internet Things J.*, vol. 3, no. 4, pp. 572–580, Aug. 2016.

[5] L. Mainetti, L. Patrono, and A. Vilei, "Evolution of wireless sensor networks towards the Internet of Things: A survey," in *Proc. 19th Int. Conf. Softw., Telecommun. Comput. Netw. (SoftCOM)*, 2011, pp. 1–6.

[6] J.-P. Vasseur and A. Dunkels, *Interconnecting Smart Objects With IP: The Next Internet*. San Mateo, CA, USA: Morgan Kaufmann, 2010.

[7] M. Z. Hasna, H. Al-Rizzo, and F. M. Al-Turjman, "A survey on multipath routing protocols for QoS assurances in real-time wireless multimedia sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 3, pp. 1424–1456, 3rd Quart., 2017.

[8] F. Sousa, R. Campos, and M. Ricardo, "Energy-efficient wireless multimedia sensor networks using FM as a control channel," in *Proc. IEEE Symp. Comput. Commun. (ISCC)*, Jun. 2014, pp. 1–7.

[9] J. Dias, F. Sousa, F. Ribeiro, R. Campos, and M. Ricardo, "Green wireless video sensor networks using FM radio system as control channel," in *Proc. 12th Annu. Conf. Wireless Demand Netw. Syst. Services (WONS)*, Jan. 2016, pp. 1–8.

[10] R. Campos, R. Duarte, F. Sousa, M. Ricardo, and J. Ruela, "Network infrastructure extension using 802.1D-based wireless mesh networks," *Wireless Commun. Mobile Comput.*, vol. 11, no. 1, pp. 67–89, 2011.

[11] F. Sousa, J. Dias, F. Ribeiro, R. Campos, and M. Ricardo, "A traffic-aware solution for green wireless video sensor networks," in *Proc. IFIP/IEEE Wireless Days*, Mar. 2017, pp. 1–6.

[12] F. Ribeiro, R. Campos, D. Rua, C. Pinho, and J. Ruela, "PACE: Simple multi-hop scheduling for single-radio 802.11-based stub wireless mesh networks," in *Proc. IEEE 9th Int. Conf. Wireless Mobile Comput., Netw. Commun. (WiMob)*, Oct. 2013, pp. 103–110.

[13] A. Rowe, R. Mangharam, and R. Rajkumar, "FireFly: A time synchronized real-time sensor networking platform," in *Wireless Ad Hoc Networking: Personal-Area, Local-Area, and the Sensory-Area Network*, S.-L. Wu and Y.-C. Tseng, Eds. Minneapolis, MN, USA: Auerbach, 2006, pp. 65–104.

[14] L. Gu and J. A. Stankovic, "Radio-triggered wake-up for wireless sensor networks," *Real-Time Syst.*, vol. 29, nos. 2–3, pp. 157–182, Mar. 2005.

[15] B. Van Der Doorn, W. Kavelaars, and K. Langendoen, "A prototype low-cost wakeup radio for the 868 MHz band," *Int. J. Sensor Netw.*, vol. 5, no. 1, pp. 22–32, Feb. 2009.

[16] E. Shih, P. Bahl, and M. J. Sinclair, "Wake on wireless: An event driven energy saving strategy for battery operated devices," in *Proc. 8th Annu. Int. Conf. Mobile Comput. Netw.*, 2002, pp. 160–171.

[17] I. Haratcherev, M. Fiorito, and C. Balageas, "Low-power sleep mode and out-of-band wake-up for indoor access points," in *Proc. IEEE GLOBECOM Workshops*, Nov. 2009, pp. 1–6.

[18] T. Mekonnen, P. Porambage, E. Harjula, and M. Ylianttila, "Energy consumption analysis of high quality multi-tier wireless multimedia sensor network," *IEEE Access*, vol. 5, pp. 15848–15858, 2017.

[19] *IEEE Standard for Information Technology Part 11, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Standard 802.11-2007, Institute of Electrical and Electronics Engineers Standard, 2007.

[20] N. Rajagopalan and C. Mala, "Modified power save model for better energy efficiency and reduced packet latency," *Amer. J. Eng. Appl. Sci.*, vol. 5, no. 3, pp. 237–242, 2012.

[21] J.-M. Choi, Y.-B. Ko, and J.-H. Kim, "Enhanced power saving scheme for IEEE 802.11 DCF based wireless networks," in *Personal Wireless Communications*, M. Conti, S. Giordano, E. Gregori, and S. Olariu, Eds. Berlin, Germany: Springer, 2003, pp. 835–840.

[22] Z.-T. Chou, "Adaptive power management technique for IEEE 802.11 wireless ad hoc networks," in *Energy Efficiency Research*, D. Bergmann, Ed. Commack, NY, USA: Nova, 2009, pp. 1–28.

[23] Y. Shi and T. A. Gulliver, "An energy-efficient MAC protocol for ad hoc networks," *Wireless Sensor Netw.*, vol. 1, no. 5, pp. 407–416, Dec. 2009.

[24] E.-S. Jung and N. H. Vaidya, "An energy efficient MAC protocol for wireless LANs," in *Proc. 21st Annu. Joint Conf. Comput. Commun. Soc.*, vol. 3, 2002, pp. 1756–1764.

[25] V. Vukadinovic, I. Glaropoulos, and S. Mangold, "Enhanced power saving mode for low-latency communication in multi-hop 802.11 networks," *Ad Hoc Netw.*, vol. 23, pp. 18–33, Dec. 2014.

[26] K. J. Olempia, C. Pandeeswaran, and P. Natarajan, "A survey on energy efficient contention based and hybrid MAC protocols for wireless sensor networks," *Indian J. Sci. Technol.*, vol. 9, no. 12, pp. 1–10, 2016.

[27] Q. Zhou, Y. Xu, and X. Li, "HTSMAC: High throughput sensor MAC for wireless video networks," in *Proc. Int. Conf. Wireless Commun., Netw. Mobile Comput. (WiCom)*, 2007, pp. 2428–2431.

[28] A. Shahzad, G. A. Shah, and A. U. Khattak, "QoS-supported energy-efficient MAC (QEMAC) protocol based on IEEE 802.11 e for wireless multimedia sensor networks," in *Proc. 5th Int. Conf. New Trends Inf. Sci. Service (NISS)*, vol. 1, Oct. 2011, pp. 200–204.

[29] X. Zhang and K. G. Shin, "E-MiLi: Energy-minimizing idle listening in wireless networks," *IEEE Trans. Mobile Comput.*, vol. 11, no. 9, pp. 1441–1454, Sep. 2012.

[30] V. Bhandary, A. Malik, and S. Kumar, "Routing in wireless multimedia sensor networks: A survey of existing protocols and open research issues," *J. Eng.*, vol. 2016, pp. 1–27, Mar. 2016. [Online]. Available: https://www.hindawi.com/journals/je/2016/9608757/

[31] S. Ratnaraj, S. Jagannathan, and V. Rao, "OEDSR: Optimized energy-delay sub-network routing in wireless sensor network," in *Proc. IEEE Int. Conf. Netw., Sens. Control (ICNSC)*, Apr. 2006, pp. 330–335.

[32] M. Chen, V. C. M. Leung, S. Mao, and Y. Yuan, "Directional geographical routing for real-time video communications in wireless sensor networks," *Comput. Commun.*, vol. 30, no. 17, pp. 3368–3383, Nov. 2007.

[33] I. Politis, M. Tsagkaropoulos, T. Dagiuklas, and S. Kotsopoulos, "Power efficient video multipath transmission over wireless multimedia sensor networks," *Mobile Netw. Appl.*, vol. 13, nos. 3–4, pp. 274–284, 2008.

[34] P. Gupta, P. Saxena, A. Ramani, and R. Mittal, "Optimized use of battery power in wireless ad hoc networks," in *Proc. 12th Int. Conf. Adv. Commun. Technol. (ICACT)*, vol. 2, Feb. 2010, pp. 1093–1097.

[35] S. Ehsan and B. Hamdaoui, "A survey on energy-efficient routing techniques with QoS assurances for wireless multimedia sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 2, pp. 265–278, 2nd Quart., 2012.

[36] I. Lee, W. Shaw, and J. H. Park, "On prolonging the lifetime for wireless video sensor networks," *Mobile Netw. Appl.*, vol. 15, no. 4, pp. 575–588, 2010.

[37] *Specification of the Radio Data System (RDS) for VHF/FM Sound Broadcasting in the Frequency Range From 87.5 to 108.0 MHz*, Européenne, Norme Standard CENELEC EN 50067:1998, Apr. 1998.

[38] J. Blanckenstein, J. Klaue, and H. Karl, "A survey of low-power transceivers and their applications," *IEEE Circuits Syst. Mag.*, vol. 15, no. 3, pp. 6–17, 3rd Quart., 2015.

[39] *CC1200 CC1200 Low Power, High Performance RF Transceiver|TI.com*. Accessed: Apr. 24, 2018. [Online]. Available: http://www.ti.com/product/CC1200/datasheet/specifications#SWRS1543749

[40] C. Aydogdu and E. Karasan, "An analysis of IEEE 802.11 DCF and its application to energy-efficient relaying in multihop wireless networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 10, pp. 1361–1373, Oct. 2011.

[41] X. Zhang and K. G. Shin, "E-MiLi: Energy-minimizing idle listening in wireless networks," in *Proc. 17th Annu. Int. Conf. Mobile Comput. Netw. (MobiCom)*, New York, New York, USA: ACM Press, Sep. 2011, p. 205.

[42] L. M. Feeney and M. Nilsson, "Investigating the energy consumption of a wireless network interface in an ad hoc networking environment," in *Proc. INFOCOM 20th Annu. Joint Conf. IEEE Comput. Commun. Soc.*, vol. 3, Jun. 2001, pp. 1548–1557.

[43] D. Halperin, D. Greenstein, A. Sheth, and D. Wetherall, "Demystifying 802.11n power consumption," in *Proc. Int. Conf. Power Aware Comput. Syst.*, Vancouver, BC, Canada: USENIX Association, 2010, p. 1.

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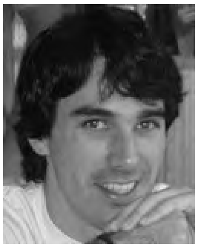

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