Green Wireless Video Sensor Networks using FM Radio System as Control Channel

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***Abstract*—The rise of the Internet of Things and the growth of the IP cameras market are making Wireless Video Sensor Networks (WVSNs) popular. In turn, Wi-Fi is becoming the enabling technology for WVSNs due to its flexibility, high bitrates provided and low cost; however, these networks suffer from three major problems: bad performance, throughput unfairness, and energy inefficiency. In order to address the lack of holistic solutions to solve these problems, we propose the FM-WiFIX+ solution. This solution uses FM radio as an out-of-band control channel to signal when a video sensor should turn its IEEE 802.11 interface OFF, thus saving energy.**

The results obtained with a proof-of-concept prototype show that for a network with 7 nodes the proposed solution can achieve gains of energy up to 48 %, while maintaining good levels of performance and throughput fairness.

***Keywords*—Energy-efficiency, FM Radio Data System, Network Performance, Out-of-band Signaling, Wireless Video Sensor Networks.**

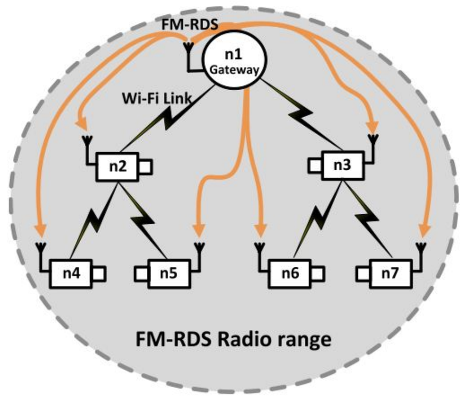

Fig. 1: FM-WiFIX reference scenario [4].

I. Introduction

Wireless Sensor Networks (WSNs) have revolutionized the way of retrieving data from the environment, enabling a wide range of new applications in fields such as healthcare, agriculture, military, and security. Moreover, the current trend is to use the Internet Protocol (IP) to interconnect WSNs with the Internet, leading to the Internet of Things (IoT) paradigm [1][2].

The majority of the current WSNs are formed by low-end sensors such as temperature, gas, and pressure sensors, which allow the detection of certain events and the retrieval of measurements. The introduction of more complex and powerful video sensors leads to new applications, as video sensors allow the retrieval of rich information and the inference of complex and new contexts [3]. A network formed by distributed video sensors is referred in the literature as a Wireless Video Sensor Network (WVSN).

In a WVSN the sensors retrieve large amounts of data in the form of video streams, which must be transferred to a gateway or a sink node, as shown in Fig. 1. In order to enable these transmissions, IEEE 802.11 is becoming increasingly the technology of choice, since it allows high bitrate communications within a hundred meters [4]. However, when applied to WVSNs it presents three major problems: poor performance, throughput unfairness, and energy inefficiency [4].

In IEEE 802.11 based multi-hop networks, the Carrier Sense Multiple Access – Collision Avoidance (CSMA/CA) mechanism is incapable of efficiently avoiding collisions, due to the presence of hidden nodes. The RTS/CTS mechanism employed to avoid the hidden node problem, should not be used in mesh networks since it introduces the exposed node problem. It has been shown that the use of RTS/CTS in mesh networks may even be counterproductive [5][6]. This brings up the poor performance problem caused not only by the hidden nodes but also by the backoff mechanism of CSMA/CA.

Another consequence of the network's multi-hop nature is the monopolization of the medium by the nodes closer to the gateway, in detriment of the leaf nodes, which will likely enter in starvation [7]. This leads to the throughput unfairness problem.

Finally, the energy problem is once more related to the CSMA/CA mechanism. The network interface is always ON, even when not transmitting or receiving any information, and idle listening is the dominant mode of energy consumption [8].

The lack of solutions to solve these problems in a holistic manner has motivated the development of the FM-WiFIX+ solution, which aims precisely at solving the three problems and is based on the FM-WiFIX conceptual solution [4]. The FM-WiFIX+ solution integrates former solutions, WiFIX [7] and PACE [6], and together they provide an holistic solution to

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overcome the three problems mentioned above in the context of WVSNs. WiFIX is in charge of efficiently forming and maintaining a wireless mesh network. The PACE scheduling mechanism ensures that: 1) only one packet is in transit in the whole network at each moment, thus avoiding collisions; 2) that each node has exactly one transmission opportunity per transmission round, thus assuring throughput fairness. Finally, the new FM-RDS based out-of-band control channel introduced by the FM-WiFIX conceptual solution, enables the improvement of the energy efficiency of the network by turning OFF the sensors' Wi-Fi interfaces while they are waiting for their transmission opportunity defined by the PACE scheduling mechanism.

Our contributions are three-fold: 1) we propose the FM-WiFIX+ solution, featuring an FM-RDS out-of-band control channel and the scheduler in the gateway; 2) we demonstrate how the FM-WiFIX+ solution can be deployed on a real WVSN; 3) we evaluate the solution on the assembled testbed and prove the feasibility of the FM-WiFIX concept [4] by quantifying the actual gains achieved.

The rest of this paper is organized as follows. Section II presents the existing solutions to solve the three problems mentioned, with focus on the energy inefficiency problem. Section III provides an overview of the FM-WiFIX concept. Section IV describes the FM-WiFIX+ solution, including the registration phase, polling mechanism, and adopted FM-RDS messages format. Section V describes the assembled testbed, the experiments conducted and the results obtained. Section VI presents the main conclusions of this work and guidelines for the future work.

II. Related Work

In order to assure the validity and the relevance of this work, a survey on solutions similar to FM-WiFIX was conducted.

There are many examples of solutions that, by using an out-of-band control channel, are able to reduce a system's power consumption. The design methodology for PicoRadio Networks [9] presents interesting guidelines to achieve energy efficiency in sensor networks. The platform proposed in [10] uses an AM signal to globally synchronize the network nodes in a TDMA scheme, where the nodes are sleeping outside their transmission time slot. In [11] the authors propose a radio-triggered circuit, powered by the radio signals; when there is no reception of suitable radio signals, the circuit is shut down and so is the sensor. A custom technology for implementing these out-of-band control channels is implemented in [12] but operating only for small ranges. The solutions presented in [13][14], 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 idle state. They show how ambitious the goal of our work is, as our objective is to apply a low-power, out-of-band control channel for a system where state transitions of the wireless card must be signaled every few milliseconds. To the best of our knowledge a control channel with these requirements was never implemented before in the context of wireless sensor networks.

The Wi-Fi Power Saving Mode (PSM) defined in the IEEE 802.11 standard [15] is not suitable for the proposed scenario for two reasons: 1) the overhead introduced is high if applied to multi-hop networks; 2) in a video surveillance system, the cameras have always data to transmit, thus they would never enter in sleep state. Although the first problem is solved in [16], the second problem prevents the use of the IEEE 802.11 PSM in a WVSN.

Since many of the WVSN problems are related to the medium access control mechanism employed, it makes sense to address these problems by improving the MAC protocols. In [17] a concept similar to FM-WiFIX is proposed, where nodes enter in sleep mode and the medium access control mechanism defined guarantees that video streams are transmitted in the network with no collisions. However, it only works in multimedia sensor networks, retrieving different types of data apart from video; the QEMAC protocol, proposed in [18] to improve the fairness and energy-efficiency of the standard IEEE 802.11e has no use in WVSN for the same reason. An interesting mechanism is the one presented in [8], where during the idle listening periods imposed by CSMA/CA the nodes down-clock their Wi-Fi network interface cards, thus reducing the energy consumption during those periods. The radio is in a subconscious mode during this idle listening period, without losing the capacity of promptly responding to incoming packets. However, there is still margin for improvement, since the Wi-Fi radios can be completely shut down, as explained in Section III concerning the FM-WiFIX.

Finally, there are the energy-efficient routing techniques. This is the most popular approach found in the literature to address the energy inefficiency problem in sensor networks and many solutions are proposed specifically for the context of Wi-Fi based WVSNs. Different strategies are employed. The solutions proposed in [19][20][21][22] use the information about the energy levels of the various network nodes to make routing decisions that extend the network lifetime. Since these protocols are proposed for networks specialized 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 are evidences that adding mobile sensors in WVSNs may improve their performance, including coverage and energy efficiency [23]. Therefore, another major approach followed is the use of a mobile sink. In [24] a solution that aims at prolonging the WVSNs lifetime is proposed, where the mobile sink approach is combined with hierarchical and energy-aware routing.

III. The FM-WiFIX Concept

Combining well-known concepts and strategies, the FM-WiFIX concept [4] addresses the three main problems of WVSNs in an innovative way, standing out from the state of the art approaches.

To build and maintain the WVSN, FM-WiFIX relies on WiFIX. Wi-Fi Network Infrastructure eXtension (WiFIX) is a simple and efficient routing solution, proposed in [7] to extend Wi-Fi wired infrastructures. The learning mechanisms of the IEEE 802.1D bridges are reused to handle frame forwarding and a protocol based on the periodic flooding of Hello messages is responsible for the network self-organization into a logical tree topology, rooted at the Internet gateway (see Fig. 1).

In order to avoid collisions and assure throughput fairness, FM-WiFIX reuses the PACE scheduling mechanism. In PACE [6], the gateway node is responsible for scheduling all the transmissions in the network. This requires an initial registration phase, where every node sends a registration message to the gateway, as soon as it chooses a parent node in the tree rooted at the Internet gateway. Upon the reception of this message, the gateway adds the new node to its polling list. Then, the gateway polls each node exactly once in each round, using a polling request message, which also contains the data addressed for the node being polled. This message is forwarded downwards until its destination is reached. Upon reception of the polling request, the polled node sends a polling response to the gateway, containing its data. With PACE, the reception of a message is seen as a token to transmit, which means that no node will take the initiative of transmitting by itself.

The innovation of the FM-WiFIX concept is the improvement of the network's energy efficiency. This is accomplished by the definition of an out-of-band control channel, based on the FM Radio Data System (RDS), and a modified scheduling mechanism, based on PACE. Conceptually, this mechanism works as follows. The gateway broadcasts an RDS message that contains the MAC addresses of all nodes in a given branch of the tree that should turn their Wi-Fi radio ON. After the successful reception of a packet from the leaf node of that branch, or a timeout, the gateway sends another RDS message, telling the leaf node to switch its Wi-Fi interface OFF and the transmission opportunity is given to the parent of the leaf node. This continues until the end of that branch is reached; then, the algorithm moves on to another branch of the tree.

IV. The FM-WiFIX+ Solution

A new solution named FM-WiFIX+, presented in this paper for the first time, was developed based on the FM-WiFIX concept. The bootstrap of the network starts with a registration phase. In order to minimize the amount of information to be transmitted the gateway assigns to each node, at the registering phase, an 8-bit identifier; this enables a network consisting of up to 256 nodes. The assignment of these IDs avoids the use of MAC addresses, six times bigger, as defined in the FM-WiFIX concept, which considerable improves the efficiency of the control protocol. The intermediate nodes between a given node and the gateway learn the IDs of their descendants by snooping the registration ACK message sent by the gateway, where the 8-bit identifier is assigned to the newly registered node. In order to include this feature in FM-WiFIX+, a new message was added to the PACE registration phase – the registration acknowledgment message, which also introduces more reliability to the registration process.

After the registration phase the polling mechanism starts. A solution to mimic the PACE's polling mechanism was proposed using the FM-RDS channel. An RDS message is sent in each polling request. The message contains the identifier of the node, assigned in the registration phase, to which the transmission opportunity is granted. When receiving a polling message addressed to one of its children, the intermediate nodes also turn their Wi-Fi interfaces ON, ensuring a transmission path from the transmitting node to the gateway. Similarly, when hearing a polling message not addressed either to itself or to one of its children, the node switches its Wi-Fi interface OFF. This avoids the need of control messages to turn Wi-Fi OFF.

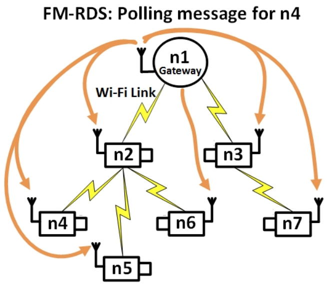
According to the FM-WiFIX concept, the scheduling mechanism should guarantee that each node is polled once every round and the Wi-Fi state changes are minimal; the toggling between ON and OFF introduces some overhead, which must be reduced to a minimum. Since the network has a tree topology, a suitable manner of achieving a polling order with the listed properties is by using the post-order tree traversal. Since this implies that the gateway must know the entire network topology, during the registration phase, each intermediate node appends to the registration message its MAC address, in order to have the gateway learning the active network topology.

Fig. 2 exemplifies the proposed scheduling mechanism. It illustrates how the nodes switch their Wi-Fi interfaces ON and OFF, according to the control message being broadcast, and the polling order adopted. The depicted behavior continues to repeat itself during the system operation. With this solution, the fairness provided by PACE is kept and the reception of the RDS message by the polled node acts as a trigger for data transmission.

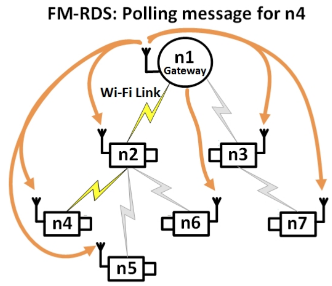
There is, however, a limitation related to the use of the RDS control channel to run the FM-WiFIX+ scheduling mechanism. The standard states that the RDS bitrate must be precisely $1187.5\,\text{bit/s} \pm 0.125\,\text{bit/s}$ [25]. Since the standard also specifies RDS groups of $104\,\text{bit}$ and each polling request requires the generation of an entire RDS group, it would take $\frac{104\,\text{bit}}{1187.5\,\text{bit/s}} \approx 87.58\,\text{ms}$ to send a polling request. This results in a packet rate of ≈ 11.4 packets/s, which decreases the network's maximum throughput to unacceptable levels and makes the control channel the system's bottleneck.

In order to overcome this limitation, the FM-WiFIX+ polling mechanism is based on burst transmissions. Instead of transmitting one packet per polling opportunity, a node continuously transmits packets, until the reception of a new RDS message or a timeout occurs. If the node has data to receive, then it turns its Wi-Fi interface ON, waits for the polling with data from the gateway, and then starts its burst transmission. The modified solution is depicted in Fig. 3.

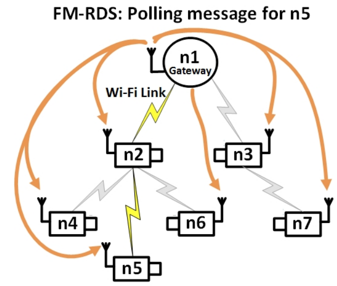
The purpose of this approach is the reestablishment of the network performance enabled by PACE, despite the limitations of the FM-RDS technology. The generation time of the RDS



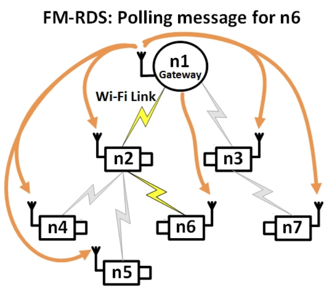
(a) Bootstrap of the FM-RDS scheduler. All nodes have their Wi-Fi interface ON and the first node polled is n4.



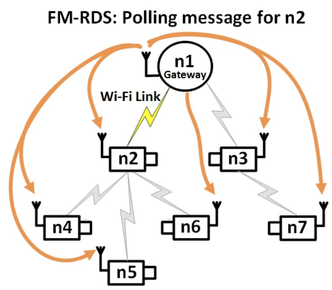
(b) Upon reception of the RDS polling message to node 4, only n4 and n2 remain with their Wi-Fi interface ON. The others turn it OFF as they are not needed for transmitting, receiving or relaying data.



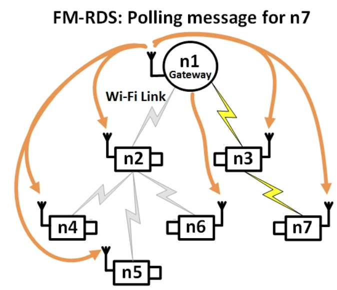
(c) As n5 receives a polling message addressed to its ID, it turns its Wi-Fi interface ON. Since n5 is not a descendant of n4, n4 turns its Wi-Fi interface OFF.



(d) n6, the last descendant of n2 is polled. Similarly to the last two scenarios, only n2 and its child are with the Wi-Fi interface ON.



(e) n2 is at 1 hop from the gateway, so only n2 has the Wi-Fi interface ON.



(f) The next node to poll, following the post-order tree traversal, is n7. Therefore, n7 and n3 (its parent) turn their Wi-Fi interfaces ON.

Fig. 2: Video sensors switch their Wi-Fi interfaces ON and OFF according to the broadcast of RDS control messages. After n7, the gateway would poll n3 and then the process returns to (b).

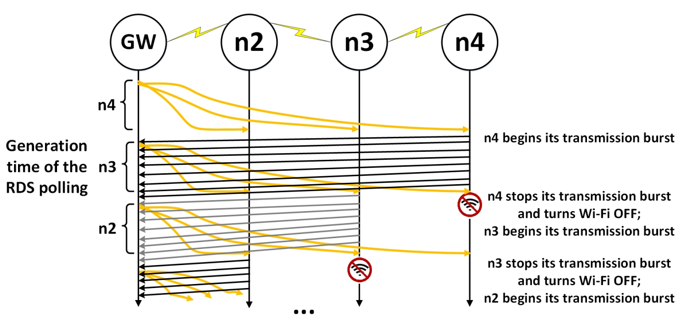


Fig. 3: The modified polling mechanism employed. For each polling opportunity assigned, a node starts a burst transmission and only stops upon reception of a new RDS message or if a timeout occurs.

messages is used for burst transmissions, instead of being wasted, thus boosting the system's performance, as desired.

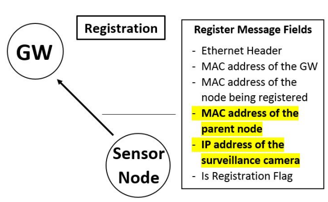
On the other hand, the FM-WiFIX+ polling mechanism is in this way better adjusted to the asymmetric traffic pattern of our WVSN; this new, ascendant traffic pattern is preferred over the previous, symmetric pattern, as the sensor nodes have much more data to transmit to the gateway than to receive. A burst transmission for each polling message received fits into the WVSN paradigm.

Within a real-time video transmission scenario, the jitter and delay are important metrics to take into account. The FM-WiFIX+ polling mechanism ensures low jitter values, due to the burst transmissions, and almost fixed delay between bursts.

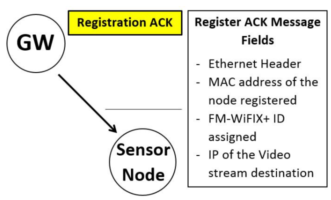
Finally, concerning the main purpose of this work, – energy savings – this approach provides a performance level that is similar to the FM-WiFIX conceptual solution. At each instant, the majority of the network nodes will have their Wi-Fi interface OFF. Since the nodes with their Wi-Fi OFF will not reply to the Hello messages exchanged by the distributed topology refresh mechanism employed by WiFIX, the nodes in power saving state will mistakenly be considered as being offline, and removed from the tree and from the polling list. Powering down the Wi-Fi interfaces also interferes with the Address Resolution Protocol (ARP). While all the protocols and mechanisms employed by the WiFIX, PACE and FM-WiFIX+ operate at the data link layer, the gateway and the video sensors must have IP connectivity to exchange the video streams and remotely control the video sensors. However, in this context, it is highly probable that the node that should reply to the ARP request has its Wi-Fi interface OFF. As a result, the IP address will remain unresolved.

Therefore, two features are considered. Firstly, WiFIX and PACE start running normally and build the mesh network. As soon as the topology becomes stable, the topology refresh mechanism of WiFIX stops working and the FM-WiFIX+ mechanism described in Section IV starts working along with its associated FM control channel. The network remains stable during most of the time; but, if some change happens, the gateway uses a failure detection mechanism to overcome the problem: if the topology must be updated, the gateway sends a Topology Refresh RDS message, ordering the nodes to stop FM-WiFIX+ and return to the combined WiFIX and PACE operation mode. WiFIX will then rebuild the network, while PACE ensures that video streams interruption is minimized. Once the network becomes stable again, FM-WiFIX+ returns to its regular operation. Secondly, information is added to the registration messages, allowing the static resolution of IP addresses and eliminating the problem associated with the exchange of ARP requests and replies.

Fig. 4 shows the modified registration protocol that enables many of the new features proposed.



(a) The content of the modified register message.



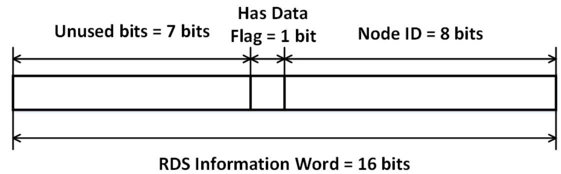
(b) The content of the new register acknowledgment message.

Fig. 4: The differences between the new registration protocol and the original, as proposed in [6], are highlighted.

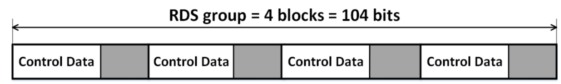
A. RDS Control Channel

The FM-WiFIX concept considers the FM Radio Data System [25] as the associated out-of-band control channel. This choice was motivated by the low-cost, low consumption and high range of FM radios. However, the solution proposed in [4] does not specify how the RDS control should be implemented. The standard specifies frames of 104 bit, divided in 4 blocks where each block contains an information word (16 bit) and a checkword (10 bit). In our control protocol, 9 bit were used: 8 bit for the node ID and 1 bit for a flag that indicates if a video sensor has data to receive. If the video sensor has data to receive, it turns its Wi-Fi interface ON and waits for a regular polling request with data from the gateway; otherwise, it immediately sends its data after hearing an RDS polling request containing its ID. For information redundancy purposes the same control information is repeated in the four blocks that form an RDS group, taking advantage of the extra space in each frame. The structure of the RDS frame and the fields used for our control protocol are depicted in Fig. 5.

Details about the implementation of the FM-WiFIX+ solution may be found in [26].



(a) The information word format of each RDS block in the control protocol. There are 7 unused bits that could be used for future improvements of the control protocol.



(b) Redundant RDS message. Each block contains the same control data. The format of the control information field is shown in Fig. 5a. The gray area corresponds to the check bits of each block.

Fig. 5: FM-RDS scheduler designed message.

V. Results Analysis and Discussion

A. Testbed and Experimental Setup

In order to deploy a low cost WVSN prototype, the hardware chosen was the Raspberry Pi Model B, Revision 2.0 platform, along with the Wi-Fi dongle TP-LINK TL-WN823N and the Raspberry Pi's camera module. For generating the FM RDS broadcast at the gateway, the open-source program named PiFmRds [27] was used. This program turns the Raspberry Pi into an FM transmitter using its built-in Pulse-width modulation (PWM) generator. On the sensor side, the SparkFun FM Tuner Evaluation Board - Si4703 was used to receive the FM RDS broadcast, together with the open-source program RdSpi [28] for controlling the FM tuner with the Raspberry Pi. Antennas were used at the transmitter and receivers, in order to ensure the RDS reception.

The assembled testbed was composed by a gateway and six video sensor nodes (see Fig. 6 and Fig. 7), operating in Wi-Fi ad-hoc mode.

The goal of the experiments was to evaluate the performance and energy consumption of FM-WiFIX+ solution in three different scenarios shown in Fig. 7: 1) binary tree topology; 2) three hop, balanced tree topology; and 3) unbalanced tree topology. Afterwards, its gains and performance were compared to the ones achieved by PACE in the same context. Each experiment was repeated several times, in order to obtain statistically significant results and narrow confidence intervals.

The Iperf tool was used to generate traffic in every node at a constant bit rate of 350 kbit/s, which was enough to saturate the network and provide statistics about the network performance. The experiments consisted in using Iperf to generate traffic to the gateway, simultaneously from all nodes, as would happen in a real video scenario. At the gateway node, a bash script is in charge of starting an Iperf server for each client, in six different UDP ports. Each sensor node will connect to one of those ports and send its data during 60 s. At the end of each experiment, the Iperf server calculates the statistics for each sensor and saves them in a log file. Each

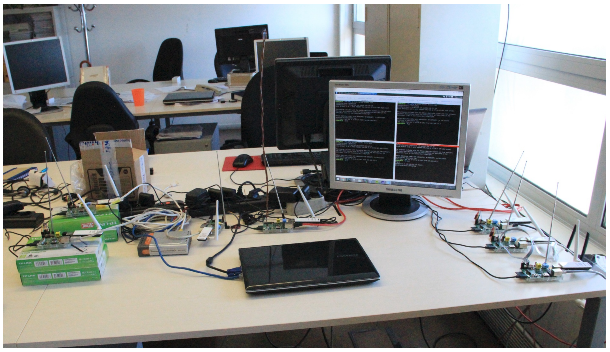
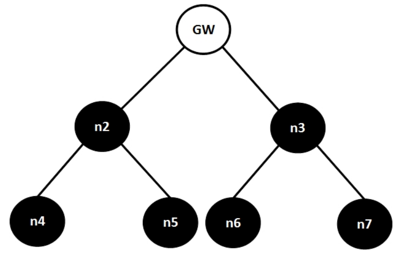
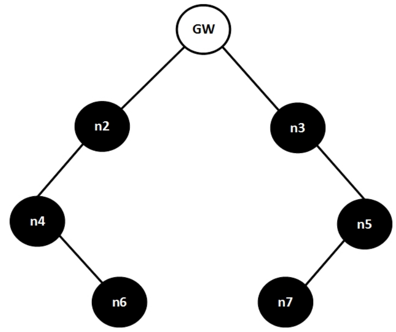


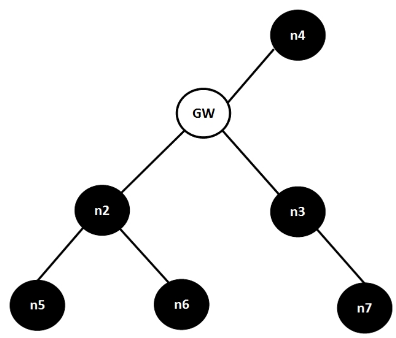
Fig. 6: FM-WiFIX+ solution testbed.



(a) Binary Tree Topology.



(b) A balanced tree topology with two branches and three hops.



(c) Unbalanced tree topology.

Fig. 7: The three scenarios used to evaluate the FM-WiFIX+ solution.

experiment was repeated 8 times for each of the scenarios shown in Fig. 7. Using the Student's t-distribution, due to the small sizes of the data sets, 95 % confidence intervals were calculated.

Since an efficient mechanism to quickly switch ON and OFF the Wi-Fi interfaces was left for future work, the power consumptions of the system were accurately measured to allow the estimation of the energy savings achieved. Initially, the power consumptions of the Wi-Fi network interface were isolated by measuring with a multimeter the Raspberry Pi's base consumption and then the power consumptions of the Wi-Fi network interface in idle state. The energy savings were then estimated by measuring the time the Wi-Fi network interface would be OFF according to the modified scheduling mechanism proposed. The measured time together with the power consumption of the Wi-Fi network interface was used to calculate the energy savings achieved.

B. Results

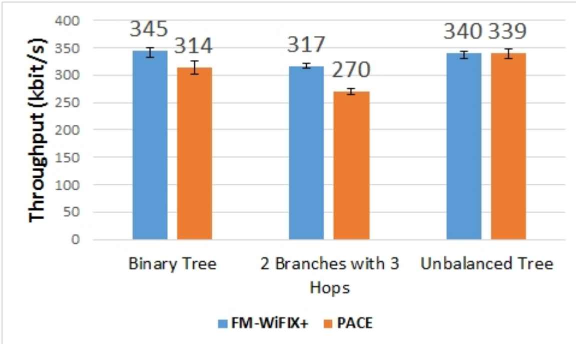
In this section the evaluation of the FM-WiFIX+ is presented. Since the WiFIX conceptual solution could not be implemented because of the limitations identified before in the paper, FM-WiFIX+ was compared with PACE solution. Fig. 8 shows the throughput and jitter obtained for both solutions and for each scenario. FM-WiFIX+ always achieves a slightly better throughput than PACE. In contrast to PACE, in the burst mechanism of FM-WiFIX+ the scheduler assigns equal time slots to all nodes. As a consequence, nodes closer to the gateway can transmit more information than leaf nodes. In PACE, every node receives exactly one polling opportunity per round, and all nodes are given the opportunity for transmitting one packet. FM-WiFIX+ guarantees equal access to the medium to every node, by giving the same time slot size to every node, but the nodes closer to the gateway can transmit more packets in the same slot than the leaf nodes. By adopting this strategy for transmitting information we enable both the increase of aggregated network throughput and node throughput fairness, as demonstrated in [26]. The throughput values obtained are very low, due to limitations of the platform used, as described in [26].

The main weakness of FM-WiFIX+ is the delay jitter exhibited. The limitations of the RDS control channel are the responsible for these poor results. However, these jitter values will not affect significantly the video streaming as buffering may always be used at the application layer [29].

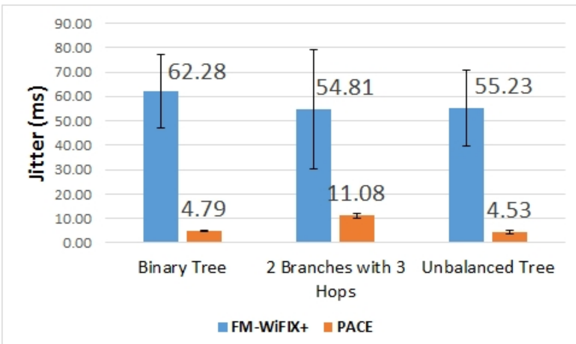
$$E_{FM-WiFIX_+} = \sum_{n=2}^{7}[P_w \cdot t_{FM-WiFIX_+}(n) + P_{FM} \cdot t_e] \quad (1)$$

$$E_{PACE} = N \cdot P_w \cdot t_e \quad (2)$$

Table I compares the theoretically and measured energy savings. These values are calculated with the ratio between the total network energy spent for FM-WiFIX+ (Equation 1) and the total network energy spent by PACE (Equation 2). $E_{FM-WiFIX+}$ is calculated by multiplying the time that each node was ON by the Wi-Fi dongle power consumption in idle state, and adding the power of all FM radios multiplied by the experiment time. E_{PACE} is calculated by multiplying the total number of nodes by the Wi-Fi power consumption and by the



(a) Throughput achieved by FM-WiFIX+ and PACE in each scenario.



(b) Jitter exhibited by FM-WiFIX+ and PACE in each topology.

Fig. 8: An overview of the performance of FM-WiFIX+ and PACE in the scenarios considered in Fig. 7.

experiment time. The theoretical values are calculated for each topology based on the turn ON and OFF sequence depicted in Fig. 2. For example in the binary tree topology nodes $n2$ and $n3$ are ON 50 %, while the rest of the nodes are ON 17 % of the time. The power consumption of the Wi-Fi dongle in idle state (750 mW) and the power consumption of the FM tuner (106 mW) used in the equations were measured during the experiment. Following the same procedure, the measured energy savings were calculated based on the $t_{FM-WiFIX+}(n)$ measured for each node during the experiment. The difference between values in the second and third scenarios may indicate that either these topologies are more susceptible to control errors or higher noise levels appeared in the RDS channel during these tests. Nevertheless, the results show that the proposed implementation of FM-WiFIX+ is indeed capable of achieving significantly energy savings in the addressed scenarios. In addition, it can be anticipated that with a more reliable control channel, higher savings could be achieved.

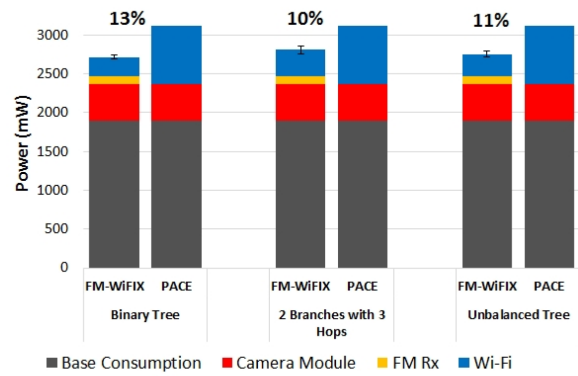
C. FM-WiFIX+ Impact in Video Sensor Energy Consumption

Concerning the power consumptions, Fig. 9 demonstrates the impact of FM-WiFIX+ in the power consumption of the video sensors, considering Raspberry Pi based video sensors and ASIC-based video sensors. In the last case, we assumed the results presented in [3], where the authors have isolated the power consumption of an ASIC-based video sensor. The

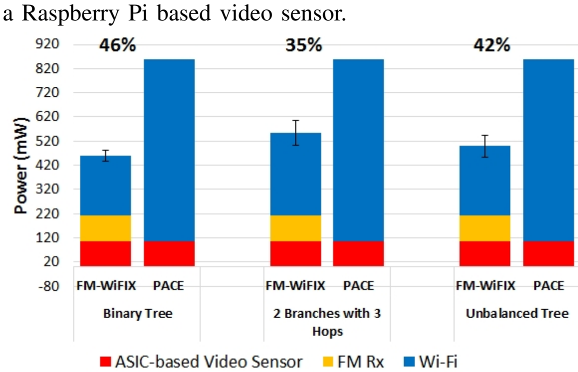
Scenario	Energy Savings	
	Measured	Theoretical
Binary Tree	53%	58%
2 Branches with 3 Hops	41%	53%
Unbalanced Tree	48%	61%

TABLE I: Energy savings estimated and measured for each scenario.

overall percentage of energy saved is presented on top of the bars. In Fig. 9b the energy savings achieved are, for the best case, 46 % but this value can increase to over 50 % by using a more reliable control channel. This conclusion is aligned with the theoretical values presented in Table I.



(a) The impact of FM-WiFIX+ in the overall power consumption of a Raspberry Pi based video sensor.



(b) The impact of FM-WiFIX+ in the overall power consumption of an ASIC-based video sensor.

Fig. 9: Impact of the FM-WiFIX+ solution considering two types of video sensors.

VI. Conclusions

In this work we presented FM-WiFIX+ and showed that it is a solution that helps solving the main problems of WVSN. As suggested by previous computer simulations and verified experimentally, it enables significant energy savings while keeping the performance achieved by PACE. It also became clear that one of the biggest limitations of the FM-WiFIX concept is the technology used for the control channel. FM

RDS is not a suitable solution for the control channel due to its low bitrate, limited range and, high error rates. Further tests with the Nordic's nRF24L01 suggest that this may be a more interesting solution. Still, thanks to the FM-WiFIX+ burst solution, good experimental results were achieved, even with the FM RDS limitations. Moreover, this method is independent of the technology used and the results reported in this paper indicate that the system's performance may be improved if other kinds of control channels are used.

We will address 4 main topics as future work: 1) study other radio technologies for the control channel; 2) assembly of a new testbed, without the processing limitations verified in the current one; 3) development of a solution to allow the swift transition between ON and OFF states of the wireless NIC, without compromising the association to the network; and 4) study how frame aggregation and spatial reuse could be used to improve the system's throughput.

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