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Protocols for Wireless Sensors Networks Connected by Radio-Over-Fiber Links

Tiago P. C. de Andrade, *Graduate Student Member, IEEE*, Nelson L. S. da Fonseca, *Senior Member, IEEE*, Leandro A. Villas, *Member, IEEE*, and Omar C. Branquinho, *Member, IEEE*

***Abstract*—Radio-over-fiber (RoF) technology has been employed in network infrastructure due to its large capacity, low attenuation, and low operational costs, as well as due to the possibility of enlarging network coverage. This paper introduces a new approach for the interconnection of wireless sensor network (WSN) by employing RoF links, specifically wireless sensor network based on radio-over-fiber (WSN-RoF). The main contribution of this paper is the introduction of an architecture for the interconnection of WSN and two medium access control (MAC) protocols exclusively tailored to WSN-RoF architecture: scheduling of polling priority MAC and dynamic hybrid MAC for WSNs based on RoF access infrastructure. Both protocols deal with the main problems in WSN-RoF, i.e., the round-trip propagation delay in optical fiber links and the existence of two distinct collision domains: one wireless and the other optical. The performance of these two protocols shows their effectiveness in the interconnection of WSN through RoF links. Results of experiments demonstrate the benefits of using RoF links for the backhaul of WSN.**

***Index Terms*—Internet of Things, medium access control (MAS) protocol, monitoring systems, radio-over-fiber (RoF) technology, wireless sensors networks (WSNs).**

I. Introduction

BACKBONE networks based on radio-over-fiber (RoF) technology [1] provide a flexible, bandwidth-efficient, and cost-effective option to fiber-based wireless access infrastructure. In RoF, the transmission of radio frequency (RF) signals occurs on optical fiber links. It is accomplished by analogically modulating a laser using RF signals [1], transmitted by a remote antenna unit (RAU), while more complex signal processing and access control are carried out at a centralized processing device, namely the base station controller (BSC) [1]. This allows the reduction of operational costs and the enlargement of the area of coverage. In addition, it leads to greater reliability when compared to conventional non-RoF connectivity [2],[3]. Moreover, a large number of already existing and underutilized optical fiber links in telecommunication networks can be used for the deployment of RoF-based networks.

This paper proposes an architecture for interconnecting wireless sensor network using RoF technology, named wireless sensor network based on radio-over-fiber access infrastructure (WSN-RoF), illustrated in Fig. 1. The proposed network architecture aims at taking advantage of the low attenuation in RoF in order to provide wider coverage for wireless sensor networks. In this architecture, each wireless sensor network (WSN) has a RAU interconnected to the BSC via an optical link. This arrangement eliminates the need for deploying several base stations by concentrating the signal processing on a single device. All the clusters are interconnected to the BSC via a shared optical link, and there is no direct communication between clusters. When a signal comes from the clusters, only the base station receives that information, but, whenever the information comes from the base station, all the clusters receive the signal. However, dealing with two collision domains (one wireless and the other optical) imposes challenges not addressed by the existing medium access control (MAC) protocols. Collisions occur in the wireless domain due to transmissions from different sensor nodes (intracluster collision), and in the optical domain due to transmissions from different clusters (interclusters collision). Moreover, the propagation delay on optical fiber links contributes to the total delay which may exceed the timing bounds existing in MAC protocols.

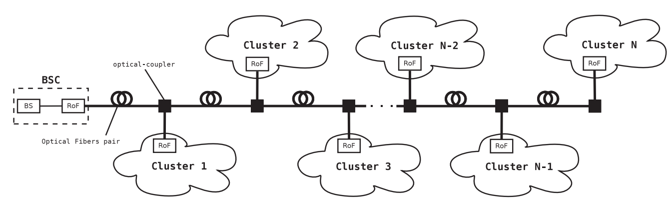

Fig. 1. Proposed architecture.

In addition, two MAC protocols exclusively tailored to the WSN-RoF architecture are presented: scheduling of polling priority medium access control (SPP-MAC) protocol and the dynamic hybrid medium access control for wireless sensor networks based on radio-over-fiber access infrastructure (D-HMARS) protocol. These protocols deal gracefully with the two collisions domains [4] ,[5] and reduce potential collisions. It will be shown that protocols that allow collision considerably degrade the performance when employed in the WSN-RoF architecture, but it does not happen when the proposed protocols are used. The WSN-RoF architecture facilitates the deployment of wireless sensor networks for monitoring and controlling large coverage areas alongside a network with bus topology such as farms along a road and sensors along Smart Grids [6]. To the best of our knowledge, no other paper in the literature introduces MAC protocols for the bus topology such as the WSN-RoF considered here [7]–[10].

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T. P. C. de Andrade, N. L. S. da Fonseca, and L. A. Villas are with the Institute of Computing, State University of Campinas, Campinas SP 13083, Brazil (e-mail: tiagoandrade@lrc.ic.unicamp.br; nfonseca@ic.unicamp.br; leandro@ic.unicamp.br).

O. C. Branquinho is with the School of Electrical Engineering, Pontifical Catholic University of Campinas, Campinas SP 13083, Brazil (e-mail: branquinho@puc-campinas.edu.br).

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The dynamic hybrid medium access control for wireless sensor networks based on radio-over-fiber access infrastructure (D-HMARS) protocol introduced in this paper differs from its predecessor version [hybrid medium access control for wireless sensor networks based on radio-over-fiber access infrastructure (HMARS)] by the introduction of a dynamic contention period. Moreover, this paper revises numerical results presented in [11]–[13], considering scenarios with much larger number of clusters and sensor nodes. It presents results related to the energy consumption of the proposed protocols which have not been shown before. Moreover, it presents, for the first time, results derived by experimentation in a testbed.

Several papers have investigated the performance of RoF-based infrastructure wireless systems. In [14], [15], the authors addressed the issue of bandwidth scarcity by using millimeter wave bands (17 and 60 GHz) for indoor local networks based on RoF links connecting distributed antennas. The work in [16]–[18] proposed solutions to the negative effects resulting from the increase of optical fiber link length due to higher request-to-send (RTS)/clear-to-send (CTS) timeout values in IEEE 802.11 networks. In [19], the authors proposed a flexible cost-effective RoF-based network architecture to support an indoor network using millimeter wave bands and the concept of extended cell. Among the papers which consider the RoF technology as a backhaul for radio networks, that in [20] presented an analysis of the use of RoF technology in IEEE 802.16 networks. Most previous work has targeted the improvement of existing protocols so they can be employed in RoF-based networks, but they have not considered the network topology as such these protocols would not be cost effective for the scenarios studied in this paper.

The remainder of this paper is organized as follows. In the next section, relevant related work is discussed. Section II introduces the proposed scheduling of polling priority medium access control (SPP-MAC) and the dynamic hybrid medium access control for wireless sensor networks based on radio-over-fiber access infrastructure (D-HMARS) protocols. Section III shows the performance evaluation of the proposed protocols based on the simulations. Section IV presents the results of experiments performed using a test bed for the scheduling of polling priority medium access control (SPP-MAC) protocol, and Section V brings final remarks.

II. Proposed MAC Protocols for WSN-RoF

This section introduces two MAC protocols for the WSN-RoF architecture. Section II-A presents the SPP-MAC protocol, a polling-based protocol, and Section II-B shows the D-HMARS protocol, a hybrid-based protocol. The employment of the SPP-MAC is adequate for supporting real-time applications such as alarm systems and multimedia applications, while the D-HMARS is more adequate for monitoring the environment.

A. SPP-MAC

The SPP-MAC is a reliable, centralized medium access control protocol based on polling that employs a prioritization mechanism to allocate an adequate number of transmission opportunities to each sensor node according to its need.

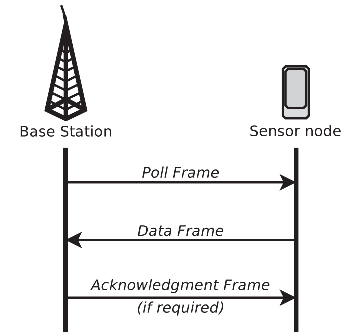

Fig. 2. SPP-MAC sensor node transmission.

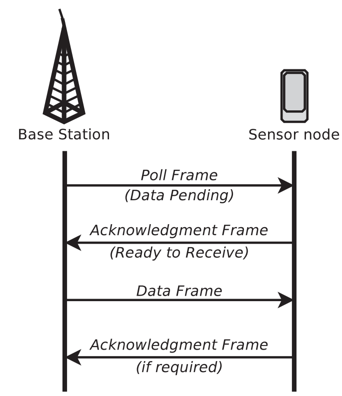

Fig. 3. SPP-MAC base station transmission.

The frame structures were designed to be minimalist, thus further reducing overhead. One important feature of the SPP-MAC protocol is that all frames are byte aligned, which means that the lengths of the frames are multiples of 8 bits. This facilitates the handling by microprocessors, which are normally designed to handle packets in units of bytes. The SPP-MAC protocol defines three types of frames: the poll frame, used by the base station for notifying the sensor node that it can transmit, the acknowledgment frame, used for acknowledging successful reception of the data and the data frame, used for all data transmission.

Figs. 2–4 show the exchange of messages between the base station and the sensor nodes. Fig. 2 exhibits a sensor node transmitting data when the base station has no data to transmit. Fig. 3 illustrates a scenario in which the base station has data to transmit. The base station informs the existence of backlogged data to the sensor node by setting a flag on the poll frame. When the sensor node receives this poll frame, it informs the base station that it is ready to receive data. This can be accomplished by using an acknowledge frame when the sensor node has no data to transmit (see Fig. 3), or a data frame when the sensor node has data to transmit (see Fig. 4).

The base station selects a sensor node for transmission by sending a poll frame to the sensor node. If the sensor node has no data to transmit, the base station notifies the next sensor node in the polling queue. The maximum waiting time is set to the round-trip delay of transmission from the most distant cluster plus the data processing time of the sensor node. To address

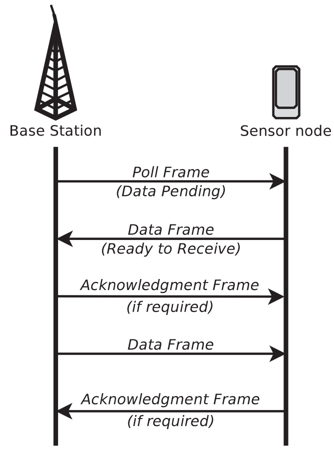

Fig. 4. SPP-MAC base station and sensor node transmission.

the need of nodes requiring more opportunities to transmit than others, the SPP-MAC protocol employs a priority policy which assigns priority values to the sensor nodes.

The base station assigns these transmission opportunities to the sensor nodes, for the establishment of a polling queue (the priority value 1 is assigned to the highest priority). The sensor nodes will thus receive $m - i + 1$ transmission opportunities in each cycle with m being the number of priority levels, and i is the priority value of the sensor node. The sensor nodes with the lowest priority value thus receive a single transmission opportunity. The total number of transmission opportunities allocated for each polling queue is given by

$$N_s = \sum_{i=1}^{m} n_i * (m - i + 1) \tag{1}$$

where i is the priority value of the sensor nodes, m is the number of priority levels, and n_i is the number of sensor nodes with priority i.

To create the polling queue, the scheduler uses m rounds. For each round, all sensor nodes with priorities from 1 to $m - \text{round} + 1$ will obtain a single transmission opportunity. The round counter is initially set to 1 and incremented by 1 after all the transmission opportunities of the sensor nodes. When the round counter reaches $m + 1$, the polling queue has been created and poll frames will be assigned to each transmission opportunity of the sensor nodes.

The SPP-MAC protocol implements a mechanism to minimize the idle-listening state. A receiver examines the destination address of a frame, as soon as it receives that destination address, even before receiving the entire frame. If the frame is addressed to any other node, the receiver immediately ceases the reception of that frame. Thus, the SPP-MAC protocol can save energy that would otherwise be wasted in unnecessary receptions, avoiding long residence times in idle-listening state. The SPP-MAC protocol enables a transceiver only when the nodes need to transmit a frame.

B. *Dynamic Hybrid MAC for WSNs Based on RoF Access Infrastructure*

The D-HMARS protocol defines an access method that combines time division multiple access (TDMA) [21] and carrier sense multiple access with collision avoidance (CSMA/CA) [21]. TDMA avoids collisions of different transmission from the sensor nodes in different clusters on the wireless channel. The D-HMARS protocol allocates each cluster to a different time period, so that, as a consequence of the adoption of TDMA, intercluster collisions are avoided. However, synchronization of the clocks of the network devices is necessary, as well as prior knowledge of the network topology by the base station to allocate the time slots. D-HMARS does not impose any restriction on the choice of mechanism for clock synchronization. Therefore, no specific mechanism is assumed in this paper.

The D-HMARS protocol employs a modified CSMA/CA mechanism to minimize intracluster collisions, with monitoring of the wireless channel prior to each data transmission. The dynamic nonpersistent CSMA/CA mechanism uses random-exponential backoff to reduce the probability of collisions. Before each data transmission, the sensor nodes and the base station must assess the condition of the channel, only starting transmission if the wireless channel is idle.

The dynamic nonpersistent CSMA/CA mechanism employs three variables. These involve the number of times a backoff is required for the current transmission (NB), the window length of the current contention (CW), and the current backoff exponent (BE). These variables are initialized upon the arrival of a new frame to transmit, with NB set to 0, CW to macCW and BE to macMinBE (with macBE and macMinBE being protocol parameters, Lines 1, 2, and 3 of Algorithm 1).

Data transmission is delayed for a random number of complete backoff periods units from 0 to $2^{\mathrm{BE}} - 1$ (Line 5 of Algorithm 1) and then a clear channel assessment (CCA) is performed (Line 6 of Algorithm 1) to check the condition of the wireless channel.

If the channel is busy, NB and BE are incremented by one, as long as the value of BE does not to exceed the macMaxBE value, and CW is set to the macCW value (Lines 12 , 13, and 14 of Algorithm 1). If the value of NB is less than or equal to the value of macMaxCSMABackoffs, data transmission is reattempted after a random number of complete backoff periods units from 0 to $2^{\mathrm{BE}} - 1$ (Line 6 of Algorithm 1). However, if the value of NB is greater than the value of macMaxCSMABackoffs, data transmission is reported as having failed (Line 16 of Algorithm 1).

If the channel is idle, the possible expiration of the congestion windows is verified. This involves decreasing the CW by one (Line 8 of Algorithm 1) and, then checking whether the new CW value is now zero (Line 9 of Algorithm 1). If it is, data transmission starts immediately; if not, data transmission is delayed by a random number of complete backoff period units from 0 to $2^{\mathrm{BE}} - 1$ (Line 5 of Algorithm 1), and a new CCA is performed (Line 6 of Algorithm 1).

The D-HMARS protocol defines two types of frames: the beacon used by the base station to transmit the scheduling

Algorithm 1: Dynamic non-persistent CSMA/CA

$CW = macCW$;
$NB = 0$;
$BE = macMinBE$;
while $TRUE$ **do**
  $random\_backoff(2^{BE} - 1)$;
  $channel = PHY\_CCA()$;
  if $channel == IDLE$ **then**
    $CW = CW - 1$;
    if $CW == 0$ **then**
      return *TRUE*;
  else
    $CW = macCW$;
    $NB = NB + 1$;
    $BE = min(BE + 1, macMaxBE)$;
    if $NB > macCSMABackoffs$ **then**
      return *FALSE*;

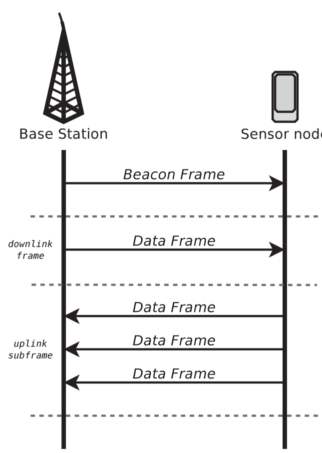

Fig. 5. D-HMARS messages exchange.

configurations of the Superframe which defines the transmission interval to the system, and the data used in all data transmissions.

Transmission is organized in rounds, and in each round, there are two phases: the setup and the execution phase. During the setup phase, the clocks of the network components are synchronized, the superframe is scheduled and the beacon frames are transmitted. In the execution phase, data are transmitted by the base station and by the sensor nodes using the dynamic nonpersistent CSMA/CA mechanism. Fig. 5 illustrates the message exchange between the base station and the sensor nodes.

The D-HMARS protocol does not employ RTS/CTS frames nor acknowledgment of reception of data frames. The avoidance of acknowledgment frames reduces the overhead as well as potential performance degradation. Moreover, it saves the time otherwise required for the reception of the acknowledgement frame, which increases with the enlargement of the optical fiber length, and it can even exceed that of data transmission.

The superframe serves as a reference for defining intervals of transmission, as shown in Fig. 6. There are two asymmetric time intervals that split the period of a superframe: the downlink

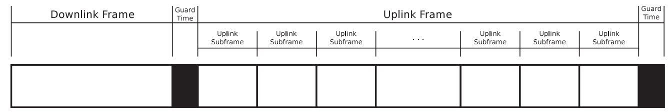

Fig. 6. D-HMARS Superframe design.

and the uplink. The downlink always proceeds the uplink and it is used by the base station to transmit data to the sensor nodes. The uplink, on the other hand, is used by the sensor nodes to transmit data to the base station. At the end of the downlink and uplink, there is a period, the Guard Time, necessary to ensure that data in a given cluster can travel over the entire optical link before the transmission of another cluster begins to transmit, thus, avoiding intercluster collisions.

To avoid the collisions between transmissions from different clusters, the uplink is divided into fixed size subframes, with each cluster assigned to a specific subframe. The sensor nodes belonging to each cluster can transmit only during the assigned subframe period. The main challenge is the allocation of the subframes to the clusters so that only a single cluster is allocated to a specific subframe, and that clusters are allocated within the uplink. After setting the superframe, the base station transmits this information to all sensor nodes by the transmission of beacon frames containing the correct information for each cluster. After receiving the beacon frame, each sensor node computes the duration of the superframe, in order to estimate when to receive data from the base station, when to transmit data to the base station, and when to resynchronize the clocks as well as the rescheduling the superframe.

Each sensor node monitors the channel waiting for clock synchronization and superframe scheduling. When a sensor node receives the beacon frame from the base station, it is informed about the global scheduling. Clock synchronization and scheduling of the superframe happen during the setup phase.

In the D-HMARS protocol, a node examines the destination address of a frame as soon as this is received. If the frame is addressed to any other node, the receiving node immediately ceases reception of that frame. Thus, the D-HMARS protocol can save energy that would have been wasted in unnecessary receptions.

III. Performance Evaluation

This section presents a performance evaluation for the proposed protocols. After the presentation of the methodology and parameter values used in the simulation, a comparison is made of the performance of the proposed protocols with the other protocols widely reported in the literature.

A. Methodology

The performance of the proposed protocols was assessed using simulations, as well as experimentation in a real testbed (Section IV). In the simulations, the network simulator 2 (NS-2) (version 2.35) [22] was used, with the simulator adapted to simulate the proposed architecture.

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TABLE I
MAIN PARAMETER VALUES OF THE SIMULATIONS

Parameter	Value
Transmission power	10 dBm
Receiver sensitivity	−95 dBm
Antenna gain	0 dBi
Transmission frequency	915 MHz
Transmission rate	250 Kbps
Modulation	GFSK
Transmit power consumption	114 mW
Receive power consumption	60 mW
Idle power consumption	18 mW
Power-down consumption	1 mW
Fiber propagation delay	5 μs/km

TABLE II
SPECIFIC PARAMETER VALUES OF THE D-HMARS PROTOCOL

Parameter	Value
macCW	2
macMinBE	3
macMaxBE	10
macMaxCSMABackoffs	7
macUnitBackoffPeriod	170 μs
macBaseFrameDuration	8160 μs
phyCCATime	85 μs
phyTurnaroundTime	75 μs

The path-loss model used was lognormal-shadowing. The reception power of the frames was compared to the sensitivity of the transceivers to decide whether or not the power received was sufficient, and the packet arrival process employed was the Poisson process.

The routing DumbAgent agent available in NS2 was used for routing in the simulations, since it is good for the assessment of medium access control protocols in the establishment of direct communication without packet forwarding messages.

All simulations were replicated 30 times with different seeds. The results are shown using confidence intervals with 95% confidence level. Data flows start at random times during the first 10 s of the simulation, i.e., the transient phase of the simulation consist of the first 10 s. The default duration of each simulation was 310 s.

The goal of the simulations was to evaluate the behavior of both the SPP-MAC and D-HMARS protocols. In the simulations, the propagation delay values of transmissions to/from different clusters consider the specific distance between a cluster and the base station. Errors in the physical layer were not considered [4], except for power loss due to signal propagation on the wireless channel. Neither physical problems caused by the use of RoF technology nor problems arising from data communication such as noise and signal attenuation in the optical link were considered. Moreover, the overhead of the physical layer was not considered.

The main parameter values for the simulations are shown in Table I, and are the same used in the experiments described in Section IV. The specific parameters for the D-HMARS protocol are displayed in Table II.

B. Metrics Evaluated

The performance metrics assessed were the *delivery ratio* of the data frames, the *effective throughput* achieved by the network and the *energy consumption*, measured as the average energy consumption per effective bit received by the base station.

The *delivery ratio* is calculated as

$$\text{Delivery} = \frac{N_{\text{received}}}{N_{\text{transmitted}}} \tag{2}$$

where N_{received} is the number of data frames correctly received by the base station and $N_{\text{transmitted}}$ is the total number of data frames transmitted by the sensor nodes to the base station.

The *effective throughput* is calculated as

$$T_{ef} = \frac{N_{\text{received}} * L_{\text{data}}}{\Delta T} \tag{3}$$

where N_{received} is the number of data frames correctly received by the base station, L_{data} is the length of the MAC payload (MSDU) of the data frame, and ΔT the total time of simulation minus the initial transient interval.

The *average energy consumption per effective bit received* by the base station is calculated as

$$E_{\text{bit}} = \frac{\sum_{i=1}^{\text{nodes}} E_i}{N_{\text{received}} * L_{\text{data}}} \tag{4}$$

where E_i is the energy consumption of the ith sensor node, N_{received} is the number of data frames correctly received by the base station, and L_{data} is the MSDU length (i.e., the length of the MAC payload).

C. Results and Discussion for Clusters With Fixed Traffic Rate

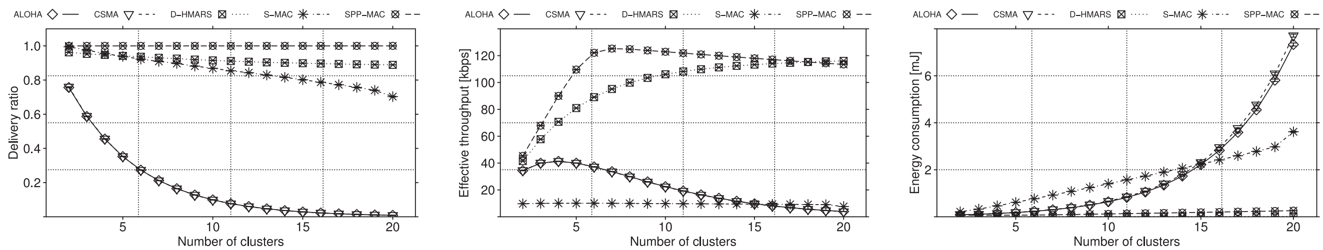
In this section, the performance of the proposed D-HMARS and SPP-MAC medium access control protocols was evaluated, and this was compared to that of three other known medium access control protocols: ALOHA, CSMA/CA, and S-MAC [7].

The sensor MAC (S-MAC) protocol [7] copes with idle-listening by repeatedly alternating periods of activity and sleep for all sensor nodes in network. During sleeping periods, the radio transceivers of the sensor nodes are turned OFF to save energy, then turned ON during active periods to exchange packets. Active periods have a fixed duration, whereas the duration of sleep periods depends on predefined duty-cycle parameter value. The S-MAC protocol deals with deafness by guaranteeing the sharing of common active periods.

In the simulations, the SPP-MAC protocol did not use the acknowledgment frame and all sensor nodes had the same priority (in this case equal to 1). For the D-HMARS protocol, the value assigned to the uplink order was 4, the value assigned to the downlink order was 15, and the value assigned to the beacon order was 15.

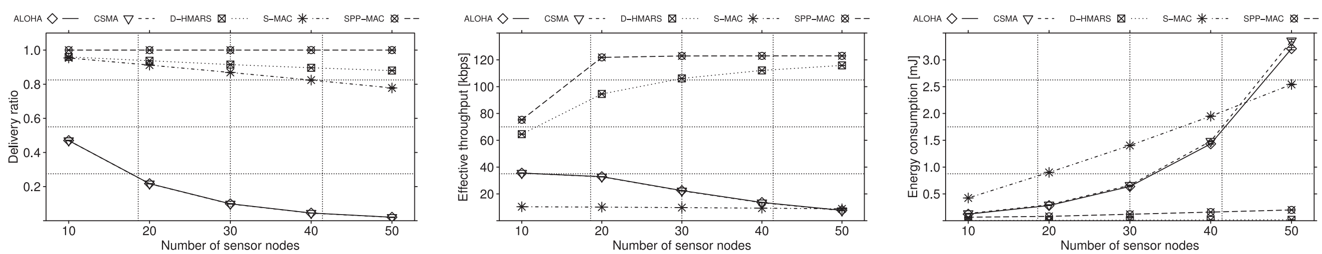
The protocols were evaluated considering three different parameters: number of clusters, number of nodes, and rate of data frame generation. For all simulations, the clusters were configured with the same traffic rate, in other words, all sensor nodes transmits with the same rate.

1) Impact of the Number of Clusters: In the scenario evaluated, each cluster was composed of 30 sensor nodes uniformly



(a) (b) (c)

Fig. 7. Impact of the number of clusters for the network using the same traffic rate. (a) Delivery ratio, (b) effective throughput, and (c) average energy consumption per bit.



(a) (b) (c)

Fig. 8. Impact of the number of sensor nodes for the network using the same traffic rate. (a) Delivery ratio, (b) effective throughput, and (c) average energy consumption per bit.

distributed within a radius of 50 m around the RAU, and the rate of data frame generation used was 2 frames/s. The number of clusters varied from 2 to 20.

Fig. 7(a) shows the delivery ratio as a function of the number of clusters. As can be seen, SPP-MAC protocol reaches 100% delivery ratio, i.e., it avoids all types of collisions (both intra- and intercluster), independent to the number of clusters. On the other hand, the D-HMARS protocol does not avoid intracluster collisions due to the occurrence of false positives in the CSMA/CA access mechanism. Many sensor nodes can transmit simultaneously hindering the precise monitoring of the channel. Most of the collisions that occur in the S-MAC protocol are intercluster ones, because an increase in the number of clusters in the system increases the number of collisions between data frames and control frames.

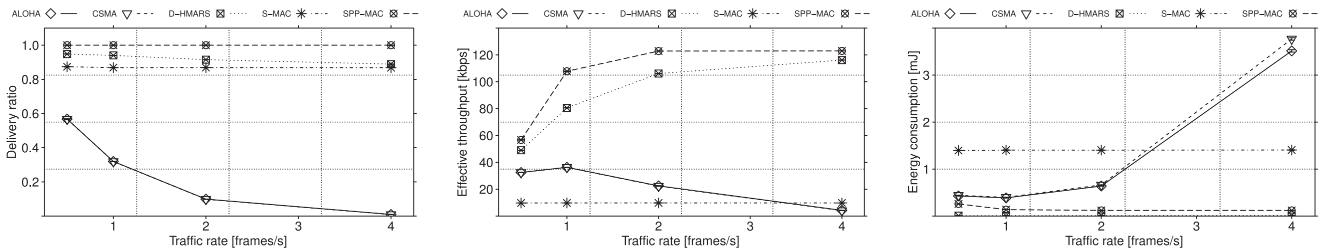
Fig. 7(b) shows the effective throughput as a function of the number of clusters. As can be seen, the SPP-MAC protocol has the highest effective throughput for less than 18 clusters (when using the configuration previously presented). When the number of clusters exceeds 18, the effective throughput of the D-HMARS protocol exceeds the effective throughput of the SPP-MAC protocol. The effective throughput of the SPP-MAC increases until a maximum value and from this point on starts to decrease. The maximum possible value of transmission rate is 125 kbps in networks with 7 clusters [see Fig. 7(b)]. This behavior is an inherent characteristic of polling-based protocols since sensor nodes can only transmit when they receive a message (poll frame) to do so. The number of messages per time unit does not increase indefinitely, and, when the maximum number of messages is reached (i.e., the base station does not send more messages inside a time period), the amount of data transmitted stays the same. However, as the length of the optical link increases with the number of clusters, the round-trip time will increase resulting in a decrease of messages being transmitted. The S-MAC protocol produces the lowest effective throughput due to the high numbers of collisions of RTS/CTS control frames.

Fig. 7(c) shows the average energy consumption per effective bit received by the base station as a function of the number of clusters. As expected, the D-HMARS protocol consumes the least energy because of the low overhead (no exchange of control messages before transmission of data) and low idle-listening periods in the protocol. The SPP-MAC protocol has a slightly higher consumption of energy due to the overhead of signalling messages (the sensor nodes need to receive the poll frame for have permission to transmit), while the S-MAC protocol has the highest energy consumption, since for every transmission an exchange of RTS/CTS control frames is needed.

The ALOHA and CSMA/CA protocols provide the worst performance. These protocols are not suitable for this kind of system, since they do not employ mechanism to avoid intercluster collisions, even though only the CSMA/CA protocol does employ an intracluster collision avoidance mechanism during transmissions.

2) Impact of the Number of Sensor Nodes: In the scenario evaluated, the number of clusters was fixed at 10, with the sensor nodes uniformly distributed within a radius of 50 m around the RAU, the frame generation rate used was 2 frames/s. The number of sensor nodes varied from 10 to 50.

Fig. 8(a) shows the delivery ratio as a function of the number of sensor nodes. As can be seen, the SPP-MAC protocol achieved 100% delivery ratio, i.e., it avoided all types of



(a) (b) (c)

Fig. 9. Impact of the traffic rate for the network using the same traffic rate. (a) Delivery ratio, (b) effective throughput, and (c) average energy consumption per bit.

collisions, even when the number of sensor nodes in each cluster increased. The D-HMARS protocol reduces the delivery ratio when the number of sensor nodes increases in each cluster, since the number of intracluster collisions increases when a large number of sensor nodes competes for access to the wireless channel. As mentioned previously, the use of the S-MAC protocol leads to too many intercluster collisions. Increasing the number of sensor nodes in each cluster increased the number of transmission attempts, and one consequence of this was a large number of control frames being transmitted, yielding more collisions and reducing the delivery ratio value.

Fig. 8(b) shows the effective throughput as a function of the number of sensor nodes. As can be seen, the effective throughput of the SPP-MAC protocol reached the maximum value of 125 kbps when each cluster had 20 sensor nodes. As expected, after this point, the effective throughput remained constant, regardless of the number of sensor nodes, since the propagation round trip delay did not increase. Thus, the same number of poll frames is transmitted by the base station and answered by the sensor nodes. For the D-HMARS protocol, even with the increase of intracluster collisions [see Fig. 8(a)], the effective throughput increased with an increase of the number of sensors nodes, tending to a maximum value. Independent of the number of sensors nodes, the effective throughput of the S-MAC protocol remained practically constant, with a value lower than those of the SPP-MAC and D-HMARS protocols.

Fig. 8(c) shows the average energy consumption per bit received by the base station as a function of the number of sensor nodes. The S-MAC protocol requires great energy consumption, since several collisions of control messages transmissions occurred, which increased the energy consumption since the control messages lost had to be transmitted again after a period exceeding the timeout value.

3) Impact of the Traffic Rate: The number of clusters and the number of sensors nodes in each cluster were fixed at 10 and 30, respectively. The sensor nodes were uniformly distributed within a radius of 50 m around the RAU.

Fig. 9(a) shows the delivery ratio as a function of the traffic rate. The delivery ratio of the S-MAC protocol remained the same for all traffic rates, which shows that the increase in traffic rate did not increase the number of collisions. The SPP-MAC protocol led to the highest delivery ratio, since the variation of the traffic rate does not affect the number of collisions. In the D-HMARS protocol, however, an increase in the traffic rate led to more false positives in the CSMA/CA access mechanism with a consequent increase in the number of collisions and a corresponding decrease in the delivery ratio.

Fig. 9(b) shows the effective throughput as a function of the traffic rate. As expected, the effective throughput of the SPP-MAC and D-HMARS protocols increased when the traffic rate increased, although, in the SPP-MAC protocol, after 2 frames/s, the effective throughput remained constant. In the SPP-MAC protocol, the sensor nodes can only transmit when the poll frame is received from the base station. Hence, when the base station reaches the maximum poll frame rate, even an increase in the traffic rate does not increase the number of transmitted poll frames and, consequently, the throughput does not increase. On the other hand, the effective throughput of the D-HMARS protocol increased, regardless of the traffic rate value.

Fig. 9(c) shows the energy consumption per bit received as a function of the traffic rate. The performance of the S-MAC protocol was constant, independently of the rate of traffic rate, which showed that the energy consumption transmission and reception of the control frames remained unchanged. The D-HMARS protocol yielded the lowest energy consumption, followed by the SPP-MAC protocol. The larger energy consumption of the SPP-MAC protocol was due to the reception of the poll frames preceding all data frame transmissions.

D. Results and Discussion for Clusters With Different Traffic Rate

In the simulations, the SPP-MAC protocol did not use the acknowledgment frame and all sensor nodes had the same priority. For the D-HMARS protocol, the value assigned to the uplink order was 4, the value assigned to the downlink order was 15, and the value assigned to the beacon order was 15. Figures in this section do not include results for the S-MAC protocol given its worst performance when compared to those of the two proposed protocols, as shown before.

The evaluation considered both the number of clusters and the number of sensor nodes. All sensor nodes in a cluster have the same traffic rate which can be one of the four predefined values (1, 2, 3, and 4 frames/s).

1) Impact of the Number of Clusters: Each cluster had 30 sensor nodes uniformly distributed within a radius of 50 m around the RAU. The number of clusters varied from 2 to 20.

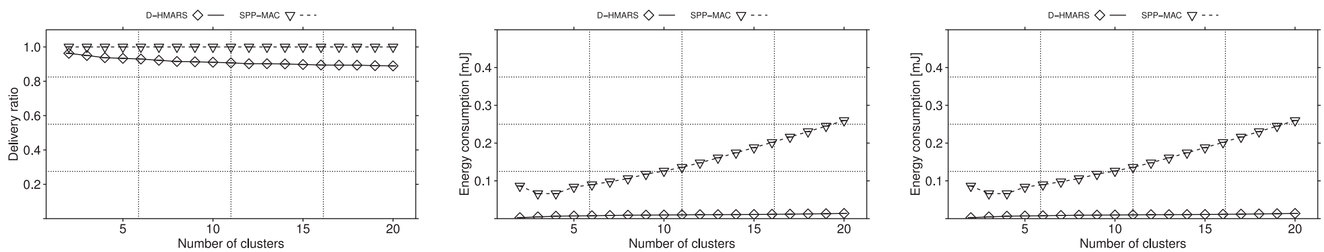


Fig. 10. Impact of the number of clusters for the network using different traffic rate. (a) Delivery ratio, (b) effective throughput, and (c) average energy consumption per bit.

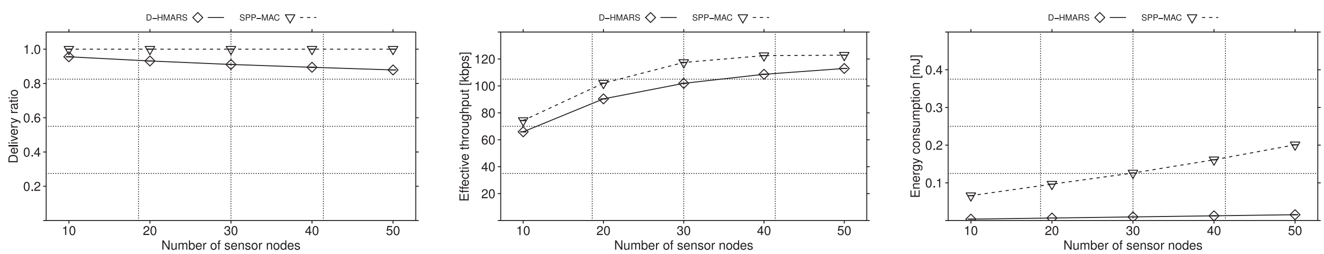


Fig. 11. Impact of the number of sensor nodes for the network using different traffic rate. (a) Delivery ratio, (b) effective throughput, and (c) average energy consumption per bit.

Fig. 10(a) shows that the SPP-MAC protocol does not produce packet loss, even when sensor nodes have different traffic rates in different clusters. On the other hand, packet loss occurs in the D-HMARS protocol due to intracluster collisions.

The throughput of the SPP-MAC has the same previously described behavior. It increases until a maximum value and then decreases when the new clusters are added to the system.

2) Impact of the Number of Sensor Nodes: The number of clusters was fixed to 10, and the sensor nodes uniformly distributed within a radius of 50 m around the RAU. The number of sensor nodes varied from 10 to 50, in steps of 10 sensor nodes.

Packet loss in the D-HMARS protocol occurs due to intraclusters collisions caused by false positives of the state of wireless channel in the CCA procedure. As the number of sensor nodes increases so do both the number of false positives and the number of collisions increase.

Fig. 11(b) shows the throughput as a function of the number of sensor nodes. The throughput does not increase continuously when the number of sensor nodes increases in each cluster for the SPP-MAC protocol. When the number of poll messages per time unit reaches a maximum value, the throughput remains constant.

IV. Experimental Evaluation of the SPP-MAC Protocol

This section presents a performance evaluation of the SPP-MAC protocol based on experimentation in a testbed. Two Arduino compatible equipment were used, one for the sensor nodes and the other for the base station. Low cost commercial RoF equipment, shielded boxes, optical fibers, optical couplers, and an antenna duplexer were also used in the experiments.

The shielded boxes prevented the arrival of the radio frequency signals of the sensor nodes at the base station, as well as that of the radio frequency signals of the base station at the sensor nodes by some path external to the RoF infrastructure being testing. This can happen due to the fact that sensor nodes and base station are located close to each other in the testbed.

In the experiment, the base station was a BE900 device employing an Atmel AVR Atmega 328 microprocessor which works as a fully functional Arduino connected to a Texas Instruments CC1101 RF transceiver. The RFBee devices were used as sensor nodes. The RFBee employs an Atmel AVR Atmega168 microprocessor and a Texas Instruments CC1101 RF transceiver. The shielded boxes used had 30 dBm attenuation and the optical fiber employed was an SMF-28 mono-mode with 0.25 dBm/km attenuation.

The performance of the D-HMARS protocol was not conducted due to both the need of providing clock synchronization and the limitation of available resources to build the testbed. Furthermore, the employment of a shielded box prevented the adoption of global positioning system (GPS) interface for clock synchronization.

A. Methodology

All experiments were replicated 10 times. The results are presented with a confidence intervals of 95% confidence level.

The network topology of the testbed is illustrated in Fig. 12. The equipment used in the testbed were shielded box of the BSC, optical fibers, shielded box of the clusters, RoF equipment working as the RAU, sensor nodes and base station, and RoF equipment.

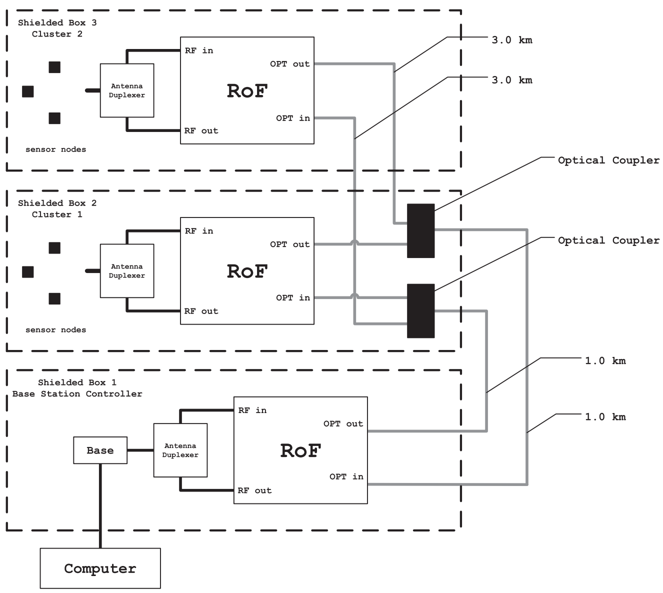


Fig. 12. Topology scheme of the experiments.

TABLE III
CONFIGURATION VALUES OF THE BASE STATION AND SENSOR NODES

Parameters	Values
Transmission power	10 dBm
Receiver sensitivity	−95 dBm
Transmission frequency	915 MHz
Transmission rate	250 Kbps
Modulation	GFSK
Transmit power consumption	114 mW
Receive power consumption	60 mW
Idle power consumption	18 mW
Power-down consumption	1 mW

Due to the limited space available for the experiments, only three shielded boxes were used: the first for the BSC, the second for the first cluster, and the third for the second cluster. The optical link between the BSC and the first cluster was 1 km long, and that between the first and second clusters was 3 km long. The total length of optical link was thus 4 km.

Since the space inside the shielded boxes was limited, the number of sensor nodes in the clusters (inside the shielded boxes) also had to be limited. Only six sensor nodes were included in each of the cluster. The number of clusters in the experiment was fixed, while the number of sensor nodes varied from 1 to 6.

The performance metrics collected during the experiment were the successful poll ratio, the effective throughput achieved by the network, and the number of dropped frames. Only the SPP-MAC protocol was implemented due to its ease implementation and the lack of need of accurate clocks. Results of the experiment showed the behavior of the SPP-MAC protocol both with and without acknowledgment frames.

The main parameter values of the equipment employed in the experiments are shown in Table III.

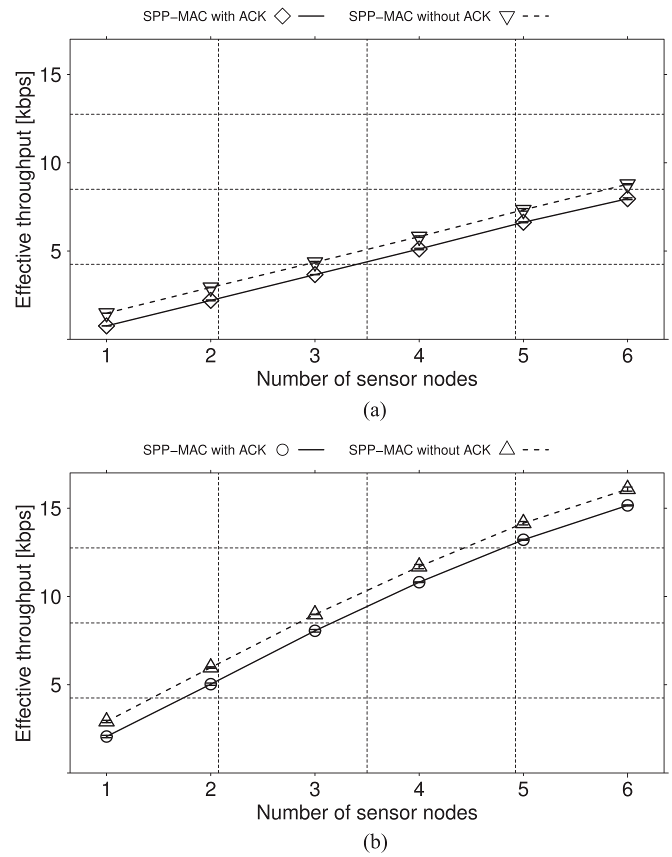


Fig. 13. Experimental effective throughput. (a) Traffic rate of 2 frames/s. (b) Traffic rate of 4 frames/s.

B. Results and Discussion

Intuitively, the delivery ratio of the SPP-MAC protocol is approximately 100% independent of the traffic rate and the number of sensor nodes in each cluster. In other words, the packet loss of the SPP-MAC protocol is a result of physical errors, not collisions of transmission from different sensor nodes. This confirms the results of the simulations, in which intracluster and intercluster collisions were completely avoided. Fig. 15 shows the number of dropped frames as a function of the number of sensor nodes. These losses are not due to collisions of the packet, but rather to physical impairments that degrade the reception quality, either from an increase in the signal attenuation or the wrong reception of one bit of data.

Fig. 14 shows the successful poll ratio (the ratio between the received packets and transmitted poll frames) as a function of the number of sensor nodes. The increase in the traffic rate, either by adding sensor nodes or by increasing the traffic rate of each sensor node, in fact, increases the successful poll ratio until it reached 100%.

To see the effects of the acknowledgment frame of the SPP-MAC protocol, a comparison of the effective throughput when the number of sensor nodes increases is shown in Fig. 13. The use of acknowledgment frame results in a lower effective throughput as the number of sensor nodes increases. This conclusion results from the fact that the transmission of the

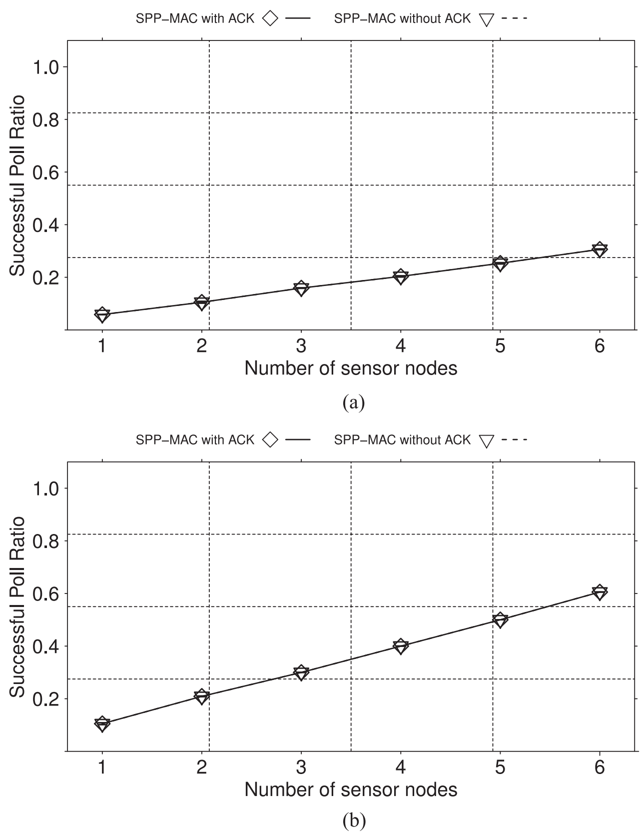


Fig. 14. Experimental successful poll ratio. (a) Traffic rate of 2 frames/s. (b) Traffic rate of 4 frames/s.

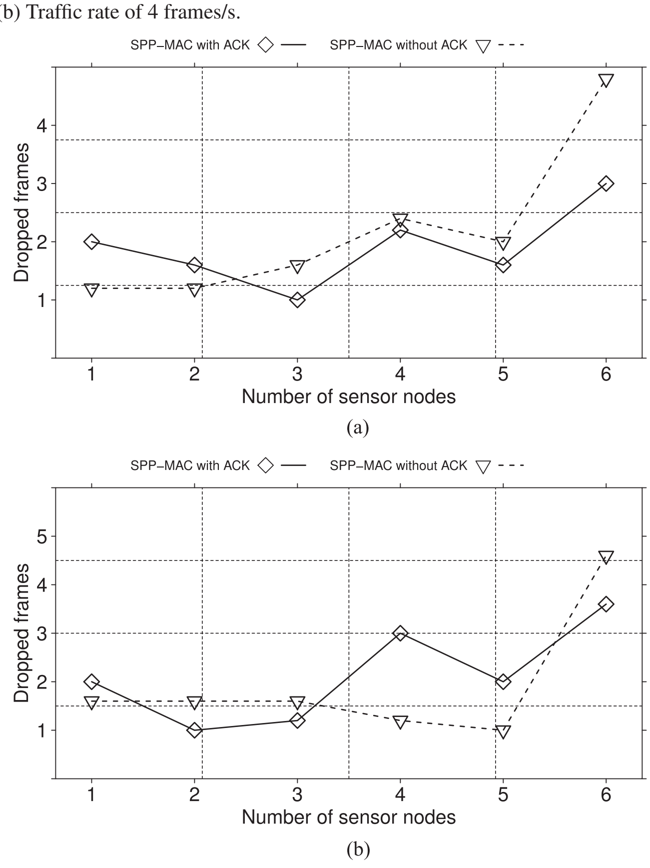


Fig. 15. Experimental dropped packets. (a) Traffic rate of 2 frames/s. (b) Traffic rate of 4 frames/s.

acknowledgment frame adds a transmission round trip delay, and during that time any other transmission can take place. Therefore, a longer period is needed between the transmission of two consecutive poll frames, thus decreasing the number of poll frames transmitted and consequently, decreasing the effective throughput. One important aspect shown in Figs. 13 and 14 is the effective throughput behavior same as the successful poll ratio, which shows that the throughput of the SPP-MAC protocol depends on the successful poll ratio.

V. Conclusion

The RoF technology permits the transmission of RF signals on optical links, allowing the joint use of wireless and optical domains. This combination makes it possible to take advantages of the two systems, thus creating a system with a large bandwidth, low attenuation, and low deployment cost.

The proposed architecture has a bus topology and integrates WSNs by connecting them via RoF links. Such architecture was designed to improve the performance of sensor networks connected by long linear extensions, for which conventional WSN is not suitable. Nonetheless, the proposed protocols deal with the challenge of managing two separate collision domains: the wireless and the optical domains. Existing medium access control protocols do not work efficiently in such architecture, but this paper has proposed two unique protocols for the WSN-RoF architecture.

To investigate the effectiveness of these proposals, simulations employing the proposed MAC protocols were conducted on networks with the WSN-RoF architecture. The simulation results were compared to those of existing protocols (ALOHA, CSMA/CA, and S-MAC). The SPP-MAC and D-HMARS protocols produced the highest delivery ratio values, increasing the effective throughput without a waste of energy, even when the traffic rate increases.

Experiments showed the feasibility of the deployment of WSN-RoF architecture using the SPP-MAC protocol. These results show similar behavior of the SPP-MAC protocol both in the simulations and in the experiments.

As future work, we plan to redesign the D-HMARS so that it can employ different subframe size defined as a function of the number of sensor nodes in the clusters.

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Tiago P. C. de Andrade (GSM’14) received the B.Sc. degree in computer science and the M.Sc. degree from the University of Campinas, Campinas, Brazil, in 2009 and 2013, respectively. He is currently working toward the Ph.D. degree in computer science at the Institute of Computing, University of Campinas.

His current research interests include sensor networks, radio-over-fiber technology, quality of service, and energy-efficient mechanisms for 4G/5G cellular networks, including machine-to-machine communications and device-to-device communications.

Nelson L. S. da Fonseca (S’86–M’95–SM’00) received the Ph.D. degree in computer engineering from the University of Southern California, Los Angeles, CA, USA, in 1994.

He is a Full Professor with the Institute of Computing, State University of Campinas, Campinas, Brazil. He has authored or co-authored over 350 papers and supervised over 60 graduate students.

Dr. Fonseca is currently the Vice President Publications of the IEEE Communications Society (ComSoc). He has served as the ComSoc Vice President Member Relations, Director of Conference Development, Director of Latin America Region, and Director of On-line Services. He was the recipient of the 2012 IEEE Communications Society (ComSoc) Joseph LoCicero Award for Exemplary Service to Publications, the Medal of the Chancellor of the University of Pisa, in 2007, and the Elsevier Computer Network Journal Editor of Year 2001 Award. He is past Editor-in-Chief of *IEEE Communications Surveys and Tutorials*. He is a Senior Editor for the *IEEE Communications Surveys and Tutorials* and the *IEEE Communications Magazine*, a member of the Editorial Board of the *Computer Networks*, *Peer-to-Peer Networking and Applications,* and the *International Journal of Communications Systems*.

Leandro A. Villas (M’16) received the Ph.D. degree in computer science from the Federal University of Minas Gerais, Belo Horizonte, Brazil, with a partial doctoral fellowship at the University of Ottawa, ON, Canada, in 2012.

He is an Assistant Professor of computer science with the University of Campinas, Campinas, Brazil. His research interests include localization and synchronization algorithms, distributed algorithms, and wireless ad hoc, vehicular, and sensor networks. He has authored several papers in the different areas of his research interests.

Omar C. Branquinho (M’13) received the B.Sc. degree in telecommunication engineering from the National Institute of Telecommunications, Minas Gerais, Brazil, in 1985, and the M.Sc. and Ph.D. degrees in electrical engineering from the State University of Campinas, Campinas, Brazil, in 1991 and 2001, respectively.

He was with the Brazilian Center for Research and Development in Telecommunications (CPqD), where he was involved with cellular and satellite networks from 1985 to 2002. He was a Brazilian representative in 3G standardization bodies. Since 2010, he has been a Professor with the Pontifical Catholic University of Campinas, Campinas. He is the creator of the Radiuino platform for sensor networks.