Wake-up Receiver based routing protocol for indoor Wireless Sensor Networks

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***Abstract*—Wake-up Receiver (WuRx) is one of the most trivial and effective solutions for energy-constrained networks and a promising solution for monitoring various phenomena in the sense of the Internet of Things (IoT). The most important and challenging issue in WuRx-based networks is the time efficient routing process in an energy efficient manner. Effectively, awaking each node needed in the routing process recursively requires a lot of time which is not suitable for time-critical applications. In this paper, we propose a novel Wake-up Receiver based routing protocol called Time Efficient WuRx-based Routing (TEW) that ensures energy optimised and time efficient routing in indoor scenarios. In our proposed approach, the network is divided into clusters at which each Fog Node manages the routes for data transmission in an asymmetric manner. When the Sink requires data from a specific set of nodes of a particular cluster, the Sink transmits a DataPts request to the corresponding Fog Node. In addition, the Fog Node sends instructions by means of a single Request (REQ) packet informing the corresponding nodes how often they should act as relays before switching to the sleeping mode. The measurement results show that our proposed approach has higher energy efficiency and achieves significant performance improvements in data delivery delay.**

***Index Terms*—IoT/WSN, WuRx, Clusters, Relays, Asymmetric Link, Routing, Latency-Minimisation, Energy-Efficiency.**

I. Introduction

Due to their robust design and self-organising networking without the need for extensive infrastructure, Wireless Sensor Networks (WSNs) are becoming very important for the IoT. This technology is widely used for monitoring and data transmission in different applications as structural and environmental monitoring [1], healthcare, as well as smart home applications, such as real-time indoor air quality monitoring [2] and on-demand indoor localisation [3]. However, the provision of wireless sensors for use in the sense of IoT is accompanied by various technical challenges [4].

Energy efficiency is the most challenging aspect in WSNs since the lifetime of sensor nodes is tightly related to its energy-critical battery. In order to allow an energy autarkic operation, a duty-cycled approach with fixed phases of transmitting, receiving, and sleeping are generally introduced [5]. Researchers, such as in [6], are promoting power management to improve the battery life of individual nodes and extend the lifetime of the entire network.

A very promising solution to face these problems is the use of an energy-autonomous, on-demand communication hardware called Wake-up Receiver (WuRx). The power consumption of a WuRx is in the order of µW whereas it is in mW for the conventional main radio [7]. In order to preserve energy, the sensor node can be set to the sleeping mode until a signal is received by the WuRx to wake up the node. Effectively, such solutions require an additional time to wake up each intermediate node sequentially when it is needed as relay in the routing process [8].

To overcome these limits, this paper proposes an energy-efficient and delay minimising routing strategy using asymmetric data transmission in a heterogeneous and clustered WSN. Our proposed approach is made up of two layers, the sensors layer and the fog computing layer. The sensors layer is made up of battery powered sensors equipped with a WuRx. The fog computing layer is made up of mains powered Fog Nodes. These nodes are located near the sensor nodes being much more powerful than sensor nodes. It maintains in its routing table all the source routes and links from each node in its cluster to it.

At the time that several Data Packets (DataPts) within a query interval needs to be exchanged, the Sink transmits a DataPts request to the Fog Node. Based on this request, the Fog Node identifies which sensor nodes should transmit DataPts to the Sink. To improve the communication on time and energy aspects, the Fog Node sends after waking up the required sensor nodes a special REQ packet. Since several DataPts are requested at the same time during this round of query, the Fog Node decides which sensor nodes are needed for DataPt routing and how often they are used as relay. This enables the use of a sensor node several times as a relay without going back to sleep mode after being used once as a relay.

We implemented the proposed strategy in a real-world

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scenario using the parameters of the WuRx developed at the Leipzig University of Applied Sciences. Evaluations show that our proposed approach has drastically optimised the energy consumption and has reduced the communication delay.

The remainder of the paper is organized as follows. Section II summarizes previous published work on Wake-up Radio assisted protocols. In Section III we explain our proposed approach and the architecture of a WSN node with a Wake-up Receiver. The comparative performance evaluation in aspects of time and energy consumption of our proposed approach called Time Efficient WuRx-based Routing (TEW) and the described approach called subsequent WuPt and REQ transmission Step-by-Step (SBS) is shown in Section IV and concludes the paper.

II. Related Work

Authors in [9] proposed a strategy for multi-hop wake-up relay in which the Collection Tree Protocol is modified to work with Wake-up Radios. If a node wants to wake up its parents two wake-up signals need to be transmitted. The first signal contains the address of the node via which the wake-up signal must be forwarded by means of the WuRx. The second signal contains the address of the destination node that the signal should ultimately reach. If the address contained in the second signal does not match with the address of a node, the node sends its own pair of WuPt signals to act as a relay. In contrast to our work, the authors of this strategy use the WuRx as a fully functional radio. They are able to receive and transmit WuPts with the WuRx while leaving the main radio in sleep mode.

A routing protocol called T-ROME is proposed in [10]. The data communication in this strategy is based on forwarding of WuPts. In this approach, based on a set of parameters, all sensor nodes have to opportunistically determine the routes themselves, in contrast to our approach where all routing information is centralised and stored in the Fog Node. The presented approach requires sending a huge number of packets for communication coordination, which has a negative impact on the overall efficiency of the network.

Researchers proposed in [11] to relay wake-up requests and reduce end-to-end data latency. Each node in the network is assigned a unique WuRx address, a unique WuRx relay address, and a broadcast WUR address shared by all nodes in the network. The relay of WuPts is requested by means of a WuRx address containing the node's unique address and an additional flag indicating that the WuPt needs to be forwarded to the receiver's own parent. The drawback of this strategy is that multiple WuPts have to be sent to wake up a single sensor node. This leads to unnecessary sendings, which are energy and time inefficient. Compared to our work, it is not necessary to send WuPts several times to make the nodes act as relays, which leads to reduce the risk of collisions and extension of communication delays.

The presented protocol, called G-WHARP [12], uses wake-up semantic addressing (energy-related aspects based on a Markov Decision Process (MDP)) to avoid waking up devices with no good forwarding availability. In this strategy, the initiator node sends a broadcast WuPt that wakes up all sensor nodes with the corresponding semantic whether they can become active and act as a relay. The sensor node that reacts first to the received WuPt by sending an acknowledgement receives the DataPt. Sensor nodes that are not required for data transmission are unnecessarily woken up to transmit acknowledgements. Even considering the MDP determination of the WuPt in advance, this leads to unnecessary energy consumption. Here, our strategy with predefined route and activation of the relays in advance using the specific REQ, presents a more optimal solution in terms of energy and latency.

In [13], authors proposed a Wake-up Receiver based routing protocol, called Clustered WuRx based on Multicast wake-up (CWM). The introduced multicast wake-up mechanism aims to simultaneously wake up the designated node for DataPt transmission and all intermediate nodes used as relays in the routing process. Measurement results demonstrate that the proposed approach exhibits higher energy efficiency and has drastic performance improvements in the delivery delay compared with the other routing protocols considered in this work. As this approach only supports a limited number of 8 cluster nodes and one Fog Node acting as link between cluster nodes and the Sink, this strategy suffers in terms of scalability. Effectively, in this approach, each node that receives a wake-up packet, returns directly to the sleeping mode when it forwards or sends a data packet. It is hence not time efficient to turn that node to the sleeping mode if it is still needed for other transmissions.

Our proposed approach overcomes these limits by indicating from the beginning to each relay how often times it will act as relay so that it will stay in the active state until forwarding all the successive packets. This would save time and energy.

III. Proposed Approach and Protocol Design

In this section, we propose a new routing strategy that ensures scalability as well as energy and time efficiency. The basic idea of our approach is to take profit of nodes that will act as relays for many successive transmissions by letting them in the wake-up state without turning them to the sleeping mode after each transmission. This would save the required time to awake them when they are needed to act as relays in future transmissions. To achieve this, the Sink starts a round by sending to the Fog Node, the set of nodes belonging to its cluster from which it needs to retrieve data. Once the Fog Node receives this request, it picks from its routing table the number of times each node in the cluster will act as relay during this round. Based on this information, the Fog Node sends to each node that will act as relay or source node a special REQ packet. This packet instructs the cluster nodes to remain active for a precise number of DataPt retransmissions and only then to switch back to the energy-saving sleep mode. This has a positive effect on time and energy efficiency.

A. Network Structure

In our proposed system, there are two types of nodes: powerful nodes (in aspects of energy and transmission power) that act as the Sink or Fog Nodes and energy-critical cluster nodes that act as cluster members. The Sink node is mains powered and is able to communicate directly with all the Fog Nodes in the network. Each Fog Node is mains powered and is able to send messages directly to every node in its cluster. Battery powered cluster nodes, on the other hand, are equipped with a WuRx and use very low transmitting power. For this reason, when a given cluster node is placed far away from the Fog Node or direct communication is not possible, intermediate nodes are needed to relay the data from that node to its corresponding Fog Node. There is hence an *asymmetric link* between each Fog Node and its cluster members.

The Fog Node maintains a routing table that contains all the source routes that are needed for efficient data communication. The sensor nodes in each cluster are equipped with a WuRx and are only activated when required by a special RF signal (WuPt). If these sensor nodes are not activated, the entire sensor node remains in sleeping mode and thus does only consume very little and negligible amount of energy. The Fog Node is the only cluster participant that enables communication between the Sink and the individual sensor nodes of a cluster. However, data communication within a cluster is possible via multi-hop. This means that the individual sensor nodes can communicate with each other and send data packets to the Fog Node using cluster nodes as relays.

B. Node Description

The sensor nodes presented in [14] and used in this work are based on commercial off-the-shelf (COTS) components. The sensor node is built out of antennas, WuRx, main radio, sensors, energy source, and microcontroller, as shown in Figure 1. The WuRx, as an additional RF reception part, has its own antenna to receive the WuPts and is configured by the microcontroller. The main receiver is used for the communication of DataPts when the sensor node is in active mode. During sleep mode, the WuRx is the only active component of the sensor node. The WuRx analyses the incoming WuPt in order to validate the address. In the case of address matching of WuPt and WuRx, the WuRx generates an interrupt signal to wake-up the microcontroller.

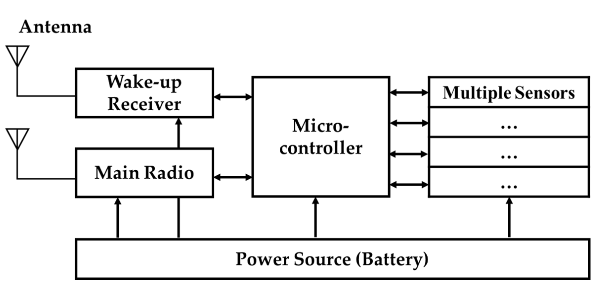

Fig. 1. A wireless sensor node equipped with a WuRx, according to [15].

C. Routing Process

When data from several nodes of a cluster is to be queried simultaneously, the communication is initiated by the Sink. It sends a DataPts request to the Fog Node which is responsible for the corresponding cluster nodes to be addressed. Based on this request, the Fog Node recognizes which cluster nodes are to be woken up for the data query. However, due to the asymmetric link, each cluster node can be woken up by the Fog Node using WuPt and a REQ can be sent, but the cluster nodes cannot send the DataPt directly to the Fog Node. So additional cluster nodes must serve as relays. Due to the simultaneous multiple polling of DataPts, our approach takes advantage of cluster nodes serving as relays multiple times without going back to sleep mode while the data packet query round continues.

The key idea of the proposed method is described in Algorithm 1. The Fog Node informs the cluster nodes which should just send its own data and which should act as relay and for how many times by means of a special REQ. This approach is intended to minimise latency and energy consumption by avoiding the cluster nodes going into sleep mode and having to be woken up or instructed again for relaying DataPts.

Algorithm 1 Request Specification

Sink requests data from different cluster nodes within one data aggregation round
Sink checks cluster table for addressing responsible Fog Node and sends a DataPts request to the Fog Node
if Fog Node receives the DataPts request **then**
    Fog Node checks cluster member table for most efficient data transmission route and sends WuPt followed by a special REQ packet to cluster nodes
    if cluster node is used only as relay **then**
        cluster node receives REQ indicating how often it will act as relay
    else
        if cluster node is requested to send only its data **then**
            cluster node receives REQ only to transmit DataPt
        else
            if cluster nodes data is requested and then the cluster node needs to relay further DataPts **then**
                cluster node receives REQ with instructions to send data and indicating how often it will act as relay

D. REQ Packet Description

The significance of the REQ packet is given by the fact that in our proposed routing approach, instructions are transmitted from the Fog Node to the sensor nodes by means of this packet. The REQ packet used in this work consists of one byte, as shown in Figure 2. This byte is divided into two sections.

The two sections differ in the interactions that the cluster node has to perform. REQs with bits set in the rear part marked in grey represent instructions which first require the sending of their own DataPt. On the contrary, REQs with bits set in the green front part specify that the cluster node only acts as a relay and does not send its own DataPt.

Packet	Action
0000 | 0000	Sending
0000 | 0001	Sending & Receiving and Sending
0000 | 0010	Sending & Receiving and Sending & Receiving and Sending
0000 | 0011	Sending & Receiving and Sending & Receiving and Sending & Receiving and Sending
....	....
0001 | 0000	Receiving and Sending
0010 | 0000	Receiving and Sending & Receiving and Sending
0011 | 0000	Receiving and Sending & Receiving and Sending & Receiving and Sending
0100 | 0000	Receiving and Sending & Receiving and Sending & Receiving and Sending & Receiving and Sending
....	....

Fig. 2. Different REQ packets of the proposed approach TEW.

IV. Experimental Setup, Measurements and Evaluation

The measurements were carried out indoor in the laboratory at the Leipzig University of Applied Sciences. The cluster size is based on 1 Sink, 1 Fog Node and 8 prototype sensor nodes acting as cluster nodes. All cluster nodes and the Fog Node are static. The Sink is located outside of the cluster. In order to get comparative results, we varied the number of times a single node acts as a relay. We compared the different strategies considering nodes relaying 3 up to 7 DataPts within one data request round and evaluated the consumed energy and the end-to-end delay.

A. Description of the Compared Strategy

We compare our proposed approach to the technique called subsequent WuPt and REQ transmission Step-by-Step (SBS). After receiving the DataPts request from the Sink, the Fog Node sequentially wakes up each cluster node used as a relay and the node intended to send the DataPt last followed by REQ packets. The REQ packets used in this strategy indicate whether the cluster node should send or receive data DataPts and thus serve as a relay in this data query round.

B. Setup

The parameters used during the experimental measurements are listed in Table I. At this point, we would like to give a note on the hardware used. For Fog Node, we have used Raspberry Pi 4 [16]. As already mentioned, off-the-shelf components were used to build the WuRx sensor node, which consist of the MSP430 [17] as the microcontroller, the SPIRIT1 [18] as the transceiver and the AS3933 [19] as the WuRx.

TABLE I
Parameter values used in this experimental measurement.

Parameter	Value
Strategies	Proposed approach TEW and SBS
Hardware	AS3933 (WuRx), SPIRIT1 (Transceiver), MSP430 (MCU), Raspberry Pi 4
WuPt	Manchester Bits (8 Carrier Burst, 6.5 Preamble, 16 Address)
DataPt	Size 107 Byte (8 Byte Preamble, 4 Byte Sync, 1 Byte Length, 1 Byte Address, 92 Byte Payload, 1 Byte CRC)
REQ	Size 18 Byte (8 Byte Preamble, 4 Byte Sync, 1 Byte Length, 1 Byte Address, 3 Byte Payload, 1 Byte CRC)
Frequency Band	868.0 MHz
Bit-Rate	AS3933 (1.16 kbit/s), Spirit (38.4 kbit/s), MSP430 (8 Mbit/s)
Modulation	AS3933 (OOK), SPIRIT1 (FSK)
Transmission power Sink and Fog Node	WuPt and DataPt (+12 dBm)
Transmission power Cluster nodes	DataPt (−34 dBm)

C. Considered Network Scenarios

In order to investigate the influence of our proposed protocol, different scenarios were considered. As shown in the following Figure 3, four different eventualities were regarded. The main difference between the scenarios is the different number of times individual sensor nodes serve as relays. The data communication increases from 3 to 7 data packets, which are transmitted and forwarded by a single cluster node acting as a relay. The yellow boxes show exactly how many DataPts are exchanged between the individual sensor nodes within one DataPts request round. The results of this study are presented in the following section.

D. Performance Evaluation

For experimental acquisition of the measurement data and the subsequent evaluation of the results, the time for data communication and the energy consumption of every single node were measured using an oscilloscope. The technical setting for the analysis also includes a shunt resistor of 1 Ω and a low noise amplifier to amplify the signal by a factor of 100. The measurement results represent the energy consumption for each node while sending, waiting or receiving a DataPts request, REQ, WuPt, or DataPt. The measurement was carried out using the described measurement setup, and the resulting outcomes are following subsequently.

Figure 4 shows the energy consumption of each node within the communication route of three data packets. A total of 9 sensor nodes were considered. More precisely, the communication extends from the Sink and the Fog Node as well as over 7 cluster nodes. As can be seen, the Fog Node has the highest energy consumption, which is due to the numerous WuPts, REQs and DataPts sent. The energy consumption of

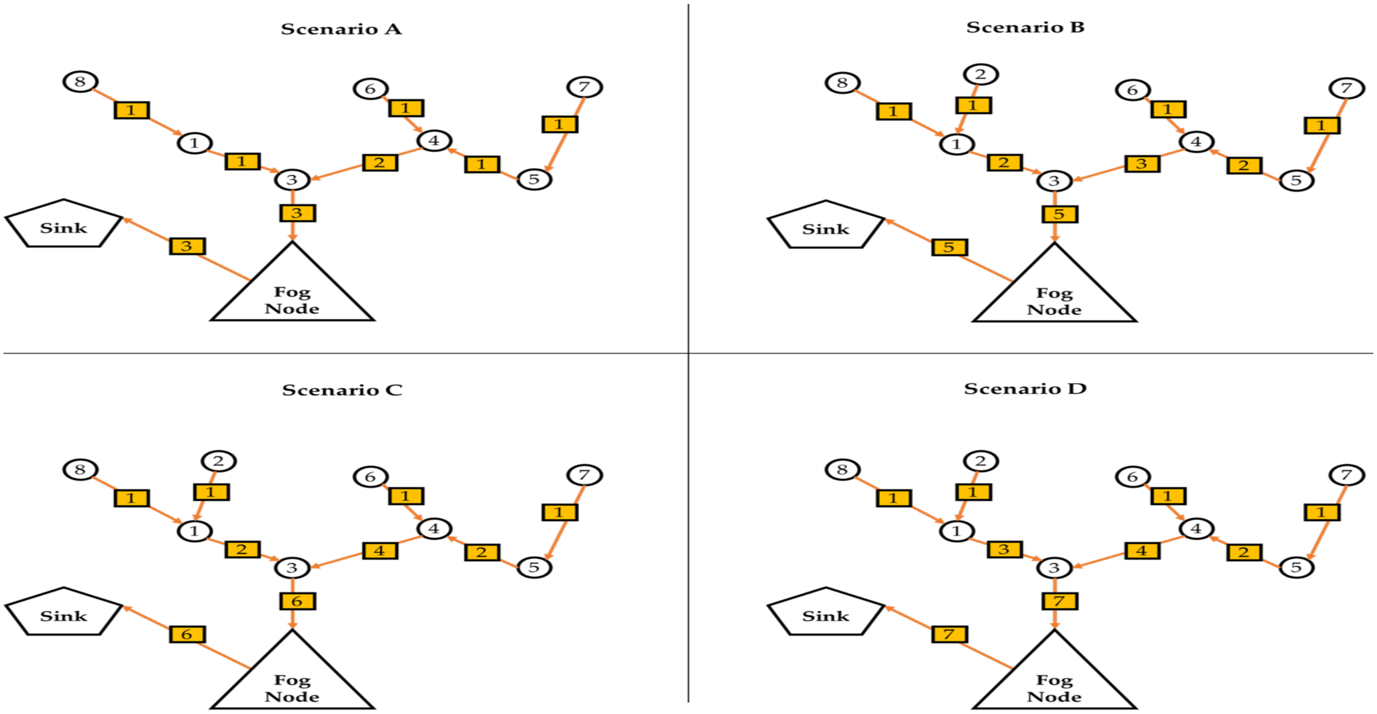

Fig. 3. The 4 Scenarios that have been considered in this research for evaluation of our proposed approach TEW and SBS.

the Sink, on contrast, is due to the time in receive mode until the end of the reception of all data packets, in this case 3 DataPts. However, since these nodes are mains powered and therefore do not have critical energy reserves, this consumption is not decisive for the longevity and operability of the network.

The nodes that only send DataPts, i.e. those that were queried by the Sink, have comparatively the same energy consumption. In this constellation, these are Nodes 6, 7 and 8. Since the actions the nodes need to fulfil are the same, they should consume the same amount of energy. This minimal difference can be attributed to a variety of reasons. Indoors, wireless sensors are generally more difficult to use due to signal fading and reflections. It should also be noted that these are measurements using prototypes that are not entirely identical to each other. Due to this fact, minimal deviations in the measurement data may occur. Since this minimal difference cannot be eliminated, and the variation has no drastic impact on the overall assessment of the measurements, this deviation may be considered negligible.

Since Node 1 and Node 5 also serve as relays only once in both strategies, they also have almost the same energy consumption. In contrast, Node 4 and especially Node 3 are noteworthy. These two nodes are used for multiple forwarding of DataPts. In total, Node 4 forwards the DataPt twice per routing strategy, and Node 3 forwards the DataPt three times per routing strategy. The slightly increased energy consumption of Node 4 is due to the fact that, using our approach TEW, the cluster node remains active in receiving mode, while in the SBS strategy the cluster node remains in sleep mode for a very short time and it is woken up again to forward the DataPt. Considering the results of Node 3, which serves three times as a relay, our proposed strategy shows its advantage. As we continue to analyse the outcomes of the measurements when adding another sensor nodes and sending more DataPts that need to be relayed, it becomes more clear that our approach offers advantages in energy consumption.

In general, if we consider the energy consumption of the individual nodes with an increase in the number of data packets that have to be forwarded by a single cluster node, a clear trend emerges. Regarding the Figures 5, 6 and 7, it becomes clear that the energy consumption of the Sink as well as of the Fog Node using the SBS approach clearly outweighs the energy consumption of our proposed approach TEW due to the time the Sink waits for the DataPts in receive mode. A more detailed analysis of energy consumption shows that Node 3 has an advantage of 2.1% in forwarding 3 DataPts with our approach compared to SBS. If 5 DataPts are forwarded from node 3, our strategy offers an energy advantage of 11.47% and when forwarding 7 DataPts even an energy advantage of 13.28%. We can hence conclude that as the size of a network increases and the Sink is used for simultaneous and multiple data requests, our strategy is advantageous in terms of energy consumption.

Considering the results in Figure 8, which shows the total overall energy consumption of the two strategies, taking into account the different frequency of DataPt forwarding, it is clear that our proposed approach TEW achieves an increase in efficiency as the number of DataPts forwarding increases.

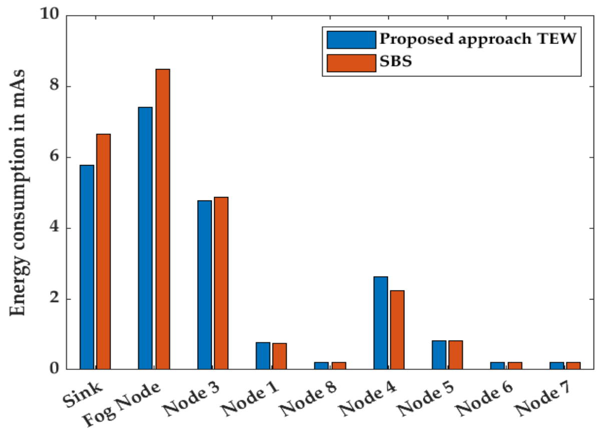

Fig. 4. Nodes Energy Consumption in Scenario A transmitting 3 DataPts.

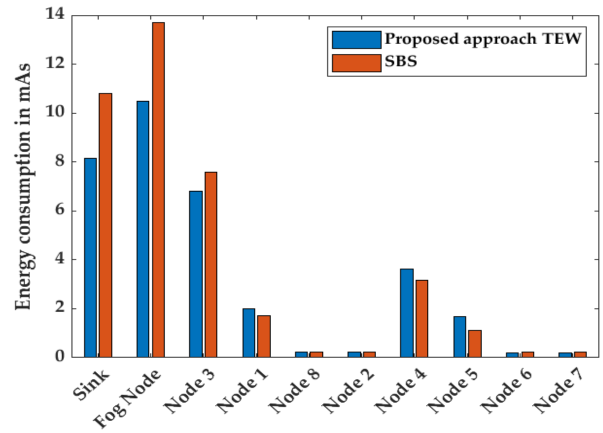

Fig. 5. Nodes Energy Consumption in Scenario B transmitting 5 DataPts.

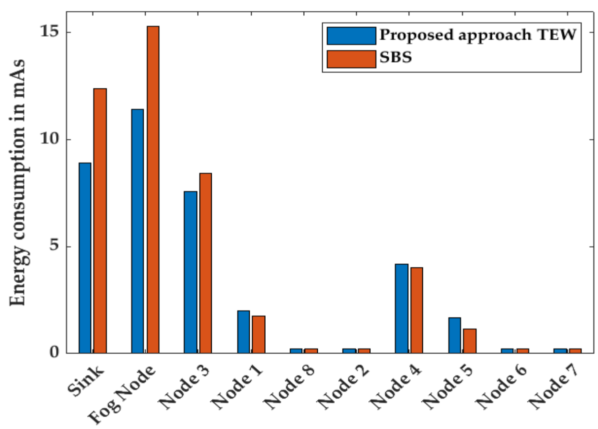

Fig. 6. Nodes Energy Consumption in Scenario C transmitting 6 DataPts.

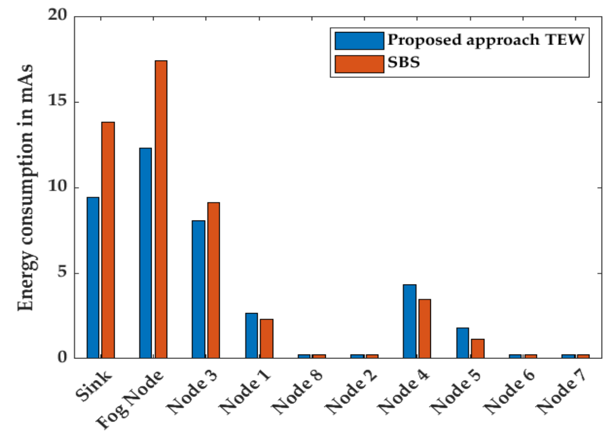

Fig. 7. Nodes Energy Consumption in Scenario D transmitting 7 DataPts.

In addition to the energy savings, Figure 9 clearly shows the benefits of our approach on time aspects. It is also clearly visible that the more data is requested by the Sink simultaneously in a query round, the lower the latency with our approach becomes in comparison to the other strategy. This can be explained by the fact that our approach keeps the nodes that will act as relays awake during the routing process, which saves the time that is needed to wake them up many times to ensure relaying activities.

Considering the time required for data communication, our proposed approach outperforms SBS by offering the best trade-off between energy efficiency and delay minimisation. The delay minimisation of our strategy in Scenario A was 14.54% compared to the SBS approach when using Node 3 as relay three times per data request round. Considering Scenario B when Node 3 is relaying 5 DataPts, the latency using our proposed strategy is minimised about 24.71% compared to the SBS approach. If we consider Scenario D, in which the data packets are forwarded six times by Node 3, we see a latency advantage of 27.34% when comparing our approach to the SBS. Looking at the final test with 7 DataPts in Scenario D forwarded by Node 3, we have an advantage of 29.31% with our approach TEW in comparison to the approach SBS.

In the following, we study the lifetime of the network considering our proposed protocol TEW as well as the other strategy SBS. The lifetime in our scenario is the time until the first node in the network is out of energy. The battery-powered cluster nodes are powered by a CR2477 coin cell with a capacity of 1 Ah at 3 V. With an occurrence of events every 5 min; the lifetime for our proposed approach in Scenario A with Node 3 acting as relay 3 times is 7.29 years, for SBS in contrary 7.05 years. Increasing the number of DataPts that need to be relayed in Scenario B with 5 DataPts results in a lifetime of 5.04 years for our proposed approach, whereas SBS results in 4.52 years. Having 6 DataPts to be relayed using Node 3 in Scenario D, the lifetime when using our approach TEW is up to 4.52 years, when using SBS is 4.07 years. With the maximum number of DataPts considered in this work, 7 DataPts to be relayed, the lifetime is 4.25 years with our proposed approach and 3.75 years for SBS.

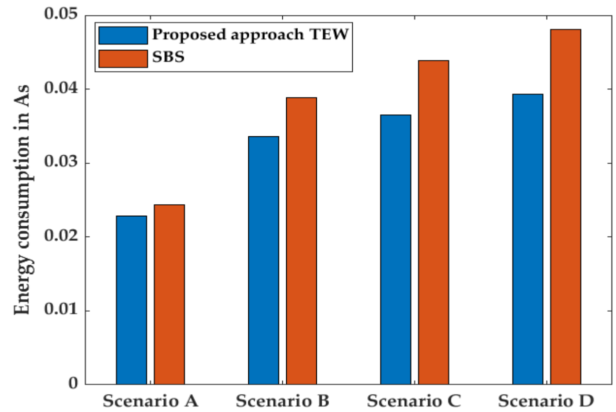

Fig. 8. Overall Energy consumption at the different Scenarios transmitting 3 up to 7 DatatPts in Scenario A, B, C and D.

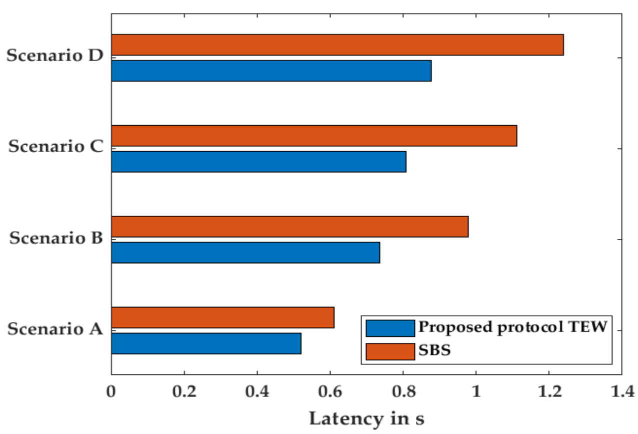

Fig. 9. Overall Time at the different Scenarios transmitting 3 up to 7 DatatPts in Scenario A, B, C and D.

E. Conclusion and Future Work

In this work, we have proposed an energy-aware and delay-minimising routing protocol for Wake-up Receiver based WSNs. Each cluster node is equipped with a WuRx in contrast to the Sink and Fog Node which has more capabilities and is mains powered. When the Sink wants to obtain data from multiple sensor nodes in a specific cluster simultaneously, it sends a request to its corresponding Fog Node. This latter wakes up the nodes that are needed to relay data packets and the intended nodes to send data packets. The nodes that act as relays are instructed by a special REQ packet that informs the nodes how often they should relay DataPts from neighbouring cluster nodes before going back to energy saving sleep mode.

Experimental results have shown that our proposed approach gives better results than the other compared strategy. Waking up cluster nodes and informing them how often they act as relay shortens delays and saves energy.

In future, we aim to enable inter-cluster communications via Fog Nodes. This has the advantage that if direct communication between a Fog Node and the Sink is not possible, communication can take place via other intermediate Fog Nodes. Furthermore, inter-cluster communication can be used to address clusters that cannot be reached directly from the Sink in large-scaled networks.

We plan also in our future work to take into account networks maintenance. As shown in our scenarios, Node 3 may become a bottleneck since it is the most used node for relaying requested DataPts. To ensure reliable data communication, it is necessary to provide alternative routes.

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