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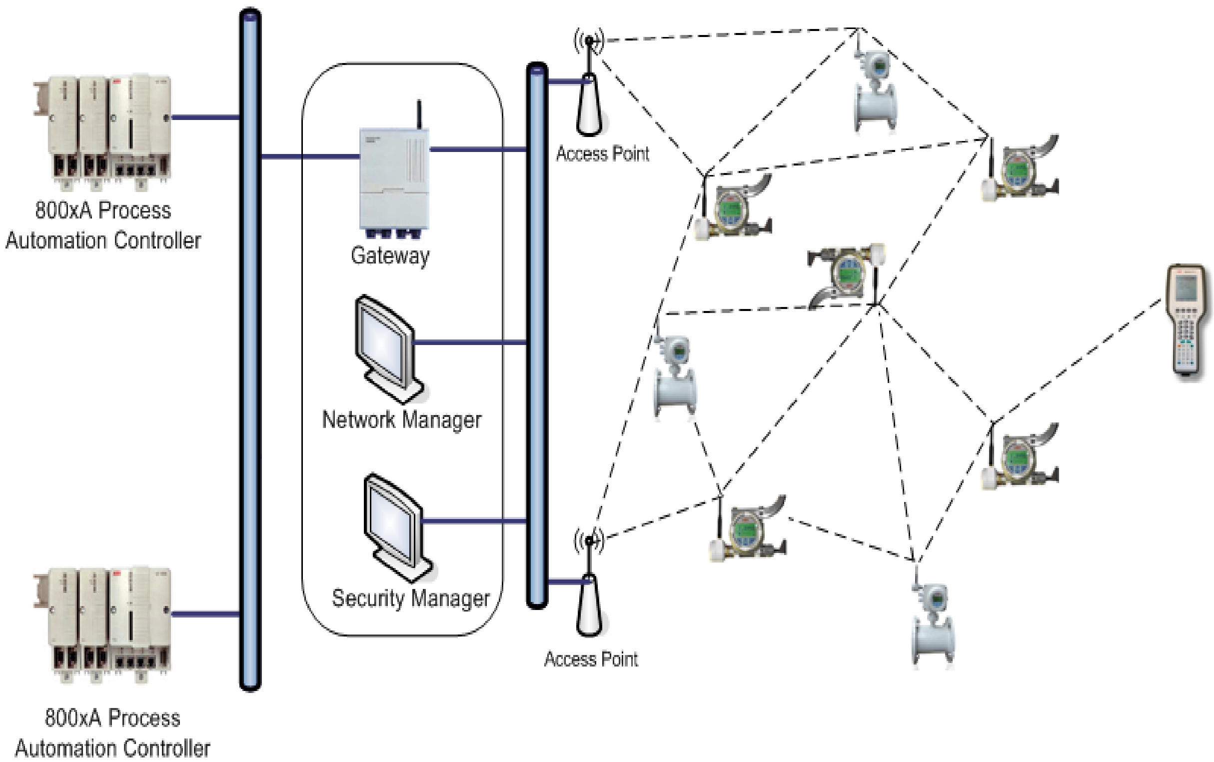

Performance Study of using Flooding in Industrial Wireless Sensor Networks

Master of Science Thesis in Communication Engineering

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PERFORMANCE STUDY OF USING FLOODING IN INDUSTRIAL WIRELESS SENSOR NETWORKS

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[Cover: An example configuration of a WirelessHART network]

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Abstract

The applications of Industrial Wireless Sensor Networks (IWSN) for Process Automation (PA) are time-critical and subject to strict requirements in terms of end-to-end delay and reliability of data delivery. A notable shortcoming of the existing wireless industrial communication standards is the existence of overcomplicated routing protocols, whose adequacy for the intended applications is questionable [4]. The aim of this thesis is to evaluate a very well known data dissemination concept of *flooding* in an industrial setting, to address the viability of exploiting flooding and discover the consequent constraints and benefits for IWSN applications. The vanilla flooding concept is recycled by introducing a number of modifications to define a location-based routing protocol, whose performance is then evaluated in the QualNet simulation environment [2]. The simulation results of all scenarios observed show that this lightweight approach is able to meet stringent performance requirements for networks of considerable sizes. Furthermore, it is shown that this solution significantly outperforms a number of conventional WSN routing protocols in all categories of interest.

Keywords: Industrial Wireless Sensor Networks, Flooding, latency, packet delivery ratio, WirelessHART.

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Finally, I am grateful to my loving parents. Their pride and happiness is my greatest reward.

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List of acronyms

ACK Acknowledgment

AES Advanced Encryption System

AODV Ad hoc On-Demand Distance Vector routing

BER Bit Error Rate

CBR Constant Bit Rate

CSMA/CA Carrier Sense Multiple Access/Collision Avoidance

DSR Dynamic Source Routing

DYMO Dynamic MANET On-demand routing

IP Internet Protocol

IWSN Industrial Wireless Sensor Network

LAR1 Location-Aided Routing version 1

MAC Medium Access Control

OLSR Optimized Link State routing

PA Process Automation

PDR Packet Delivery Ratio

PHY Physical layer

QoS Quality of Service

RSS Received Signal Strength

SNR Signal-to-Noise-Ratio

STAR Source Tree Adaptive Routing

TDMA Time Division Multiple Access

TTL Time To Live

TCP Transmission Control Protocol

UDP User Datagram Protocol

WirelessHART Wireless Highway Addressable Remote Transducer

ZRP Zone Routing Protocol

1 INTRODUCTION

1.1 Aim and Scope of the Thesis

The purpose of this work is to address one of Achilles' heels of the existing IWSN standards - real-time data delivery, i.e. average end-to-end delay. The task is to investigate the feasibility of implementing flooding in IWSNs, to pinpoint the possible trade-offs involved and to estimate the maximum network sizes that can support the offered traffic load, with respect to the timing and reliability constraints. The proposed approach is cross-layer, and all considerations are confined to uplink data dissemination.

1.2 Method

The first stage of the project is a comprehensive State-of-the-art literature study, with the aim to examine already proposed solutions for real-time data delivery in IWSNs, focusing on flooding-based and lightweight methods. The second phase is defining a lightweight routing protocol with the desired properties, followed by its implementation in the QualNet simulation environment [2]. The proposed solution is then assessed with respect to the defined performance requirements and compared with a number of existing routing protocols for ad-hoc networks, in a variety of scenarios.

1.3 Problem Statement

Industrial Wireless Sensor Networks (IWSN) for Process Automation (PA) are slowly replacing their wired counterparts. Although the penetration rate of IWSN is only several percent today, the introduction of IWSNs has taken the properties of a trend and attracts considerable attention. A recently conducted survey by ON World corporation has shown that more than half out of 105 industrial end users questioned are planning to deploy IWSN solutions over the next 18 months [41].

The main motivation for development of wireless control standards is cost reduction - the deployment costs of wired sensor networks for PA are immense, especially for off-shore installations. According to [28], wiring and installation can make up to 90% of the device cost. Another advantage of IWSNs is their ease of deployment; if the need emerges (e.g. if an industrial process is chronically misbehaving), an ad-hoc Wireless Sensor Network (WSN) can be easily set up.

The role of an IWSN is to continuously report sensor data and deliver it in real time, in order to stabilize the unstable processes and maximize the production rate. In IWSNs, the data traffic represents the sensor readings and control information from the controller to sensors and actuators. QoS in the IWSN sense translates to reliable data delivery within the predefined deadlines [25]. Typical performance requirements are listed in Table 1. They are application-specific and can only be presented in the form of a range of values.

However, the advantages of wireless control have not been fully exploited. Park *et al.* [30] identify a dichotomy in the design of existing standards, arguing that process engineers have authored the application software, while the communication engineers were responsible for the communication aspect. This, they claim, gave rise to a lack of full-picture understanding of challenges and constraints, resulting in suboptimal solutions.

A notable shortcoming of current wireless industrial communication standards is the existence of overcomplicated routing protocols, whose adequacy for intended applications is questionable [4]. The existing industrial communication standards, such as WirelessHART [1] use conventional routing protocols, which rely on routing tables and graphs and some kind of routing infrastructure, i.e. control message exchange. IWSN communication is multihop, and distributed routing algorithms are highly preferable. Data dissemination techniques used in today's industrial communication are inadequate in several aspects:

- *Path recalculation:* channel conditions vary quite rapidly in industrial environments, due to the presence of good electrical conductors, moving objects and radio interference [20]. In such a setting, link failures are frequent, so routing paths have time-limited validity. A broken link can trigger a tedious system recovery process, which leads to routing path recalculation and, consequently, long intervals of IWSN's unavailability [5]. The use of routing tables, which require building and continuous maintenance is an obstacle to flexibility.

- *Control message overhead:* the exchange of routing tables and messages used for network self-recovery or node-discovery poses a significant communication overhead.

- *Packet retransmissions:* transport layer protocols running on top of ACK-based routing protocols initiate retransmissions in case of unsuccessful packet delivery. Having in mind the high dynamics of the observed processes, the data acquired by retransmissions is most probably outdated. Common sense suggests that, instead of resending an old piece of data, transmission of a newer measurement should take place.

Thus, it is reasonable to assume that a lightweight, no-frills routing protocol could eliminate some or all of these inadequacies. Flooding is the most rudimentary routing technique, where every node in the network broadcasts all the packets that it receives or generates. The most obvious advantage of such an approach is its utter simplicity. There would be no need for exchanging control messages between the nodes and in case of link failures the routing paths would not have to be recalculated. Node failures would require no reaction from the network layer, so the transition to the new constellation would be seamless.

Another significant advantage of flooding over conventional routing protocols is that the data is delivered via multiple paths, which enhances redundancy and reliability. The routing information exchange in flooding is virtually non-existent, which leaves more traffic capacity for the actual data traffic. However, the number of multiple paths should be limited, in order to avoid the network congestion - one of the major causes of increased latency. The key is to limit the physical scope of forwarding and find the delicate balance between traffic load, speed and reliability of delivery.

1.3.1 Academia vs. Industry

One can identify numerous discrepancies between the academic approach to routing in conventional WSNs and the requirements of IWSN communication, set by the industrial community. Some of these differences are listed below, not necessarily in the order of significance.

Network size - the academic community quite often considers WSNs consisting of hundreds and even thousands of nodes. In an industrial environment, a more realistic deployment is a number of smaller, physically distributed networks consisting of tens of nodes. Each of these networks has an Access Point, which the sensor nodes deliver their measurements to, and which is connected to the Network Manager via a fast backbone. Having in mind that the maximum throughput in WirelessHART is 250 kbit/s [1], it is unlikely that hundreds of nodes could communicate via such channel, while meeting the strict deadlines listed in Table 1. Smaller IWSN deployments can greatly simplify routing and reduce the maximum number of hops in the network.

Energy consumption - the existing routing protocols often aim at optimizing the performance with respect to the energy consumption, while sacrificing latency. However, in an industrial environment, sufficient power supply is often readily available [19], and IWSN nodes are usually not battery-powered.

Downlink - the actuators are no less important than sensors in IWSN. Their job is to act upon the unacceptable behavior of the process and this downlink communication between the Network Manager and the actuators must be reliable and fast. WirelessHART standard defines a best-effort downlink, which is not acceptable in this setting. This issue and its potential solution have been thoroughly discussed in [3]. The issue of downlink is beyond the scope of this Thesis.

Node placement and spatial redundancy - contrary to generic WSNs, the node placement in IWSN is deterministic and aimed at observing particular physical phenomena. Unlike in WSNs, each IWSN sensor measurement is unique and cannot be replaced by data from another sensor.

Centralized architecture - IWSNs are centralized systems, supervised by the Network Manager, as opposed to conventional WSNs which are usually self-configurable [18].

1.4 Main Contributions

The main contributions of this work are:

- Starting from the generic form of flooding, a number of modifications is proposed in order to make it utilizable for uplink in IWSN applications.
- The performance of the proposed solution is evaluated in a WirelessHART-like network using a discrete-event simulator and it is shown that, if appropriately modified, flooding can be used as a data distribution technique in IWSNs.
- An analytical expression is given for the maximum feasible network sizes, with respect to the adopted evaluation criteria. The validity of the formula is then verified by experimental results.

Parts of this work are summarized and published in [8].

1.5 Outline

Section 1 (this section) describes the purpose and scope of this Thesis, as well as terms, abbreviations and acronyms used. It places the problem into the industrial setting and pinpoints the discrepancies between the academic and industrial approach to WSN, as well as some shortcomings of the existing WirelessHART standard. Finally, it highlights the contributions of this Thesis. Section 2 discusses the data dissemination paradigm in IWSN and presents the previous work in the area.

Section 3 discusses the proposed solution in depth. Section 4 presents the QualNet simulation environment and motivates the selection of simulation parameters. Section 5 contains the simulation scenarios and the results obtained.

Section 6 summarizes the conclusions of this Thesis. The conference paper derived from this work, which is to appear in IECON '11, is appended in Section 7. Appendices A and B contain some experiences from using QualNet, as well as node placement in the scenarios used throughout this work. The final section references the source material.

Table 1: Typical Requirements for Industrial Wireless Sensor and Actuator Networks in the Process Automation Domain [4]

Sensor Network Applications	**Delay**	**Range**	**Battery Lifetime**	**Update Frequency**	**Security level**
Monitoring and supervision					
Vibration sensor	s	100 m	3 years	sec - days	low
Pressure sensor	ms	100 m	3 years	1 sec	low
Temperature sensor	s	100 m	3 years	5 sec	low
Gas detection sensor	ms	100 m	3 years	1 sec	low
Closed loop control					
Control valve	ms	100 m	$>$ 5 years	$10 - 500$ ms	medium
Pressure sensor	ms	100 m	$>$ 5 years	$10 - 500$ ms	medium
Temperature sensor	ms	100 m	$>$ 5 years	500 ms	medium
Flow sensor	ms	100 m	$>$ 5 years	$10 - 500$ ms	medium
Torque sensor	ms	100 m	$>$ 5 years	$10 - 500$ ms	medium
Variable speed drive	ms	100 m	$>$ 5 years	$10 - 500$ ms	medium
Interlocking and Control					
Proximity sensor	ms	100 m	$>$ 5 years	$10 - 250$ ms	medium
Motor	ms	100 m	$>$ 5 years	$10 - 250$ ms	medium
Valve	ms	100 m	$>$ 5 years	$10 - 250$ ms	medium
Protection relays	ms	100 m	$>$ 5 years	$10 - 250$ ms	medium

2 BACKGROUND THEORY AND PREVIOUS WORK

The maximum transmission power in WSN is limited due to wireless network coexistence and human safety reasons. WSNs usually cover areas significantly larger than the maximum transmission range, so sensor data delivery must be accomplished via multihop communication, where routing protocols define the behavior and mutual cooperation of the nodes. Data dissemination in IWSN is significantly different from conventional communication networks [6]: the communication paradigm on the uplink (sensor to sink) communication is many-to-one, so-called *convergecast*.

Two major performance measures in IWSN are *end-to-end delay* and *packet delivery ratio* (PDR), which quantify the speed and reliability of data delivery. However, the value of average end-to-end packet delay is insufficient for assessing the IWSN performance, because jitter value excursions can be large, causing delivery of outdated measurements, although the average delay value might be in the acceptable limits. IWSN applications are time-critical and it is necessary to determine the upper bound of the delay.

2.1 Basics of IWSN and WirelessHART

WirelessHART standard, defined by the HART Foundation in September 2007, is the first standard for wireless control and process measurement [3]. The relevant entities in a WirelessHART network are [1, 34]:

- *Field devices:* Sensors and Actuators, whose role is to monitor the industrial process and act upon its behavior, respectively; some field devices only act as routers.
- *Gateway:* a single device that serves as a bond between the wireless network (which comprises field devices) and the Network Manager.
- *Access Point:* a part of the Gateway, in charge of immediate communication with the wireless network; also referred to as *sink*.
- *Network Manager:* a part of the Gateway device, responsible for configuration and maintenance of the wireless network, as well as the crucial communication issues, such as scheduling and routing.

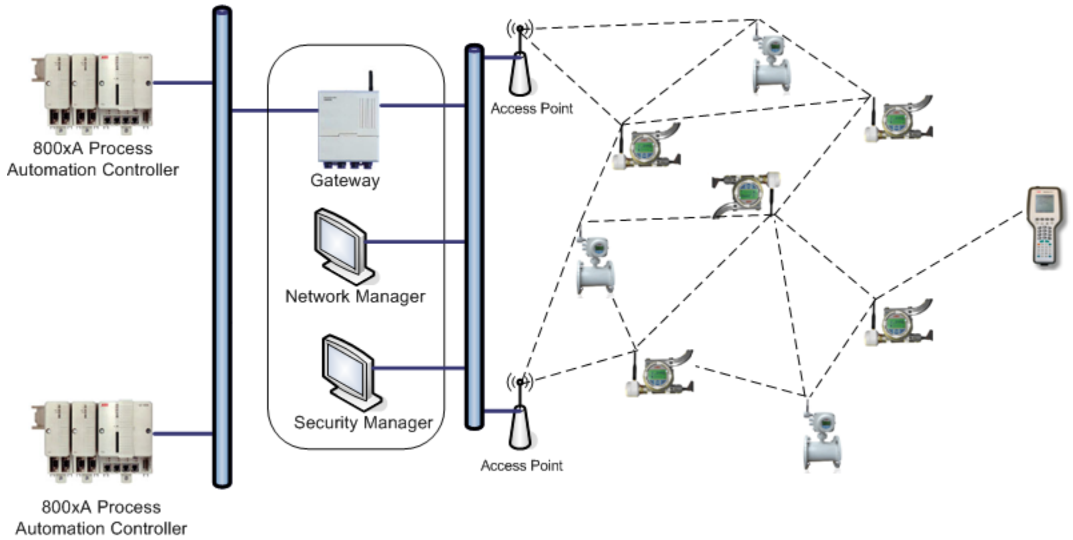


Figure 1: An example configuration of a WirelessHART network

- *Security Manager:* manages session keys and prevents possible attacks on the network by using 128-bit AES encryption.
- *Adapters:* enable communication between the wired field devices via wireless network.
- *Handheld devices:* devices operated by the factory personnel; used for diagnostics and maintenance.

WirelessHART adopts IEEE 802.15.4-2006 standard at the Physical layer, with transmission frequency in the 2.4 GHz Industrial Scientific Medical band. The data rates of up to 250 kbit/s are supported, and the system operates on one of 16 possible channels at a time. WirelessHART defines its own MAC layer [34] which is Time Division Multiple Access - based, but the frame format is in accordance with IEEE 802.15.4-2006 standard. Time is divided into superframes consisting of 10 ms timeslots. The Network Manager grants the field devices permission to send or receive, by assigning them a number of timeslots. *Dedicated* timeslots are reserved for particular transmitters, as opposed to *shared* slots, whose assignment is CSMA/CA contention-based. Frequency hopping is performed at every timeslot. In order to increase the robustness of the system, Direct Sequence Spread Spectrum technique is employed as well. The remaining layers in WirelessHART protocol stack are Network, Transport and Application layer. The observed industrial process is sampled typically every 10 - 500 ms and the measurements are reported to the Controller via Access Points.

2.2 Generic flooding

Flooding is a data dissemination technique, where a node forwards the message it has received to all of its neighbors, except to the one it received the message from. It is the simplest data forwarding technique, and its generic form exhibits a number of drawbacks [42, 29]:

- *Implosion:* multiple copies of the same packet are delivered to the sink, because a node might receive and forward the same packet twice, or a packet may travel multiple paths, getting replicated at every intermediate node.

- *Broadcast storm [38]:* flooding can produce extreme amounts of redundant traffic, due to the exponential rise in number of packets in the network after every hop. The network overload can be avoided by selective dropping of packets, but some redundancy should still remain, due to its positive effect on reliability.
- *Endless packet wandering:* due to a lack of propagation directivity, a packet can wander around the network for a long time, never reaching the destination and occupying precious network resources. This issue can be solved by limiting the Time To Live (TTL) value in the packet or by introducing the delivery deadlines.
- *Resource blindness:* this shortcoming refers to the excessive consumption of traffic resources and energy.

Due to previously mentioned reasons, flooding is rarely used as a way of conveying information *per se* in WSN. Instead, it is most often used for route discovery and setup and in the network initialization phase [43]. Watteyne *et al.* [40] claim that classical flooding is unsuitable for *convergecast*, which is the communication paradigm in IWSN and argue that flooding has latency issues, since finding the optimum routing path is usually not its primary objective.

The simplicity of flooding is non-disputable - it is an infrastructure-less, aggressive data dissemination technique. However, it requires refinement in order to exploit its potential advantages. There exist routing protocols which are based on flooding approaches and aim at removing the flooding overhead and improving energy efficiency. The consequent traffic load reduction leads to reduction of end-to-end delay as well.

2.3 Flooding-based routing protocols

2.3.1 The existing flooding-based approaches for conventional WSNs

This subsection gathers the findings of State-Of-The-Art literature study of flooding-based routing protocols for WSN. The majority of solutions eliminates broadcast storms in one of the three following ways:

1. Randomizing the packet forwarding decision - the message is forwarded only to a subset of neighbors, chosen via a probabilistic algorithm. This is the property of *Probabilistic* approaches [14], illustrated in Figure 2(a).
2. Calculating the back-off time based on some parameter, e.g RSS of the received packet or the distance traveled during the previous hop [37, 22] :

$$t_{backoff} \sim \frac{1}{f(RSS, distance)} \tag{1}$$

   This approach is depicted in Figure 2(b).

3. Threshold-based approaches compare e.g. the RSS or the distance traveled during the previous hop to a threshold, as depicted in Figure 2(c). A node shall forward the packet only if the value of RSS is below a certain value or if the previous hop is located more than a certain distance away. This distance is the radius of the red arc in Figure 2(c), and only the nodes outside the arc are allowed to retransmit the packet coming from the node located in teh center of the arc. The

Algorithm 1 The algorithm of threshold-based approaches

Receive(packet)
if $(((RSS \leq threshold) \vee (d(previous, current) \geq threshold)) = TRUE)$ **then**
    $forward(packet)$
else
    $discard(packet)$
end if
Go to waiting mode

> RSS in this sense is considered a distance indicator, meaning that its value is inversely proportional to the distance traveled during the previous hop.

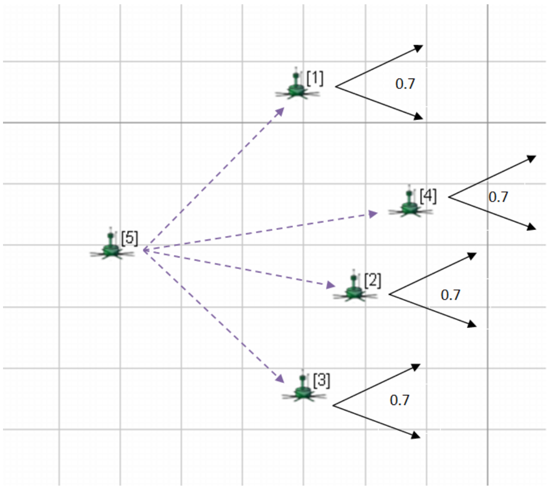
The use of flooding is frequently encountered in the WSN literature, and the conclusions are presented in Subsection 2.4.

Intanagonwiwat *et al.* [21] show that asynchronous CSMA/CA flooding exhibits high latency, but argue that flooding with TDMA on the MAC layer should perform faster, due to absence of collisions and random back-off delays. Lu and Whitehouse [26] propose an asynchronous flooding strategy, named *Flash Flooding*, and show that this technique approaches the theoretical lower latency bound, outperforming traditional latency approaches by 80%. This approach requires changes on the Physical and MAC layers and is not applicable in the sphere of interest of this work, which must employ TDMA on the MAC layer.

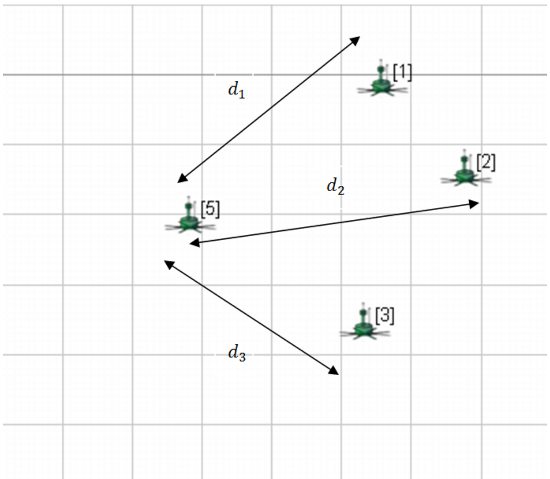
Gossiping [14] is an attempt to address the flooding overhead problem at the expense of increased delay. The forwarding node will pass the packet to a randomly selected subset of neighbors. Gossiping shows *bimodal behavior*, meaning that, for forwarding probabilities below a certain threshold, the gossiping dies out. Li *et al.* [13] claim that this threshold is between 0.6 and 0.8, for a sufficiently large network. Haas *et al.* [13] claim that gossiping sets up routes that are 10-15% longer than the ones found by flooding, for different gossip probabilities.

Flossiping [44] was proposed in order to achieve a zero-overhead resource-aware routing. It operates in two modes. In the *gossiping mode*, the sending node randomly selects a neighbor to deliver its packet to. Other neighbors receive the packet as well, and they all generate a random value, which, when compared to a predefined threshold in the packet header, will decide whether they will retransmit the packet or discard it. These neighbors are said to be in the *flooding mode*. By adjusting the threshold value between 0 and 1, Flossiping can scale to either single-branch gossiping or flooding. The main advantage is its scalability and the compromise between the power efficiency of gossiping and reduced delay of flooding.

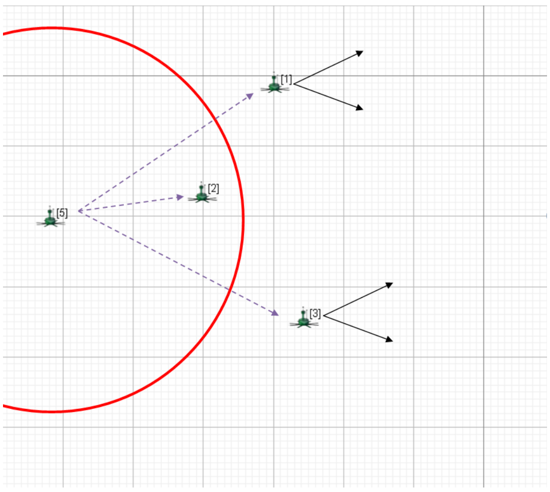
Graded Back-off Flooding [37] is a *distance-based* flooding strategy. It is a cross-layer solution, where the smaller forwarding back-off times (i.e. MAC priority) are given to the packets coming from senders further away. If the same message is heard by a node more than once, it is discarded. The distance is determined by measuring the RSS, which is not a reliable indicator, due to its intensive variations in an industrial environment.



(a) Probabilistic approach



(b) Distance-based approach



(c) Threshold-based approach

Figure 2: Different flooding based approaches

Wang *et al.* in [39] find the best retransmission candidate as the one whose retransmission would cover the largest, yet uncovered, area. This is a time-consuming procedure with high latency, and it is not convergecast, but broadcast in nature. Most importantly, it is blind - there are no guarantees that there will be any nodes in the new footprint.

Li *et al.* [13] suggest a hybrid of routing and flooding technique. The fundamental assumption is that single-path routing is unreliable and that flooding is redundant. Hence, the message is first flooded across a certain region of the network, resulting in several nodes coming in the possession of it. These nodes then use some conventional routing protocol to deliver the message to the sink along multiple paths. This protocol is primarily designed for WSN of hundreds and thousands of nodes where packets make quite long journeys. IWSNs are usually 2-3 hop mesh networks, and there is probably no time or space to shift between the two techniques during such a short journey.

Jeong *et al.* [22] propose a cross-layer counter-based flooding modification, where the distance between sender and receiver is found from the received signal strength and then used to calculate the retransmission back-off time, which is inversely proportional to the signal strength. This way, the priority is given to the transmissions that reach farthest from the source. A counter is used for duplicates of received packets and the back-off time will be directly proportional to it. One drawback of this scheme is the lack of synchronization, because the MAC layer of WirelessHART is TDMA-based and only a few slots are up for grabs. Furthermore, as previously mentioned, RSS is an unreliable measure due to its fast variation, which can result in inaccurate relative location estimate. Finally, this is a broadcast protocol and duplicate transmissions to the same node do not fit well with the strict timing requirements.

Baghaie *et al.* [7] propose *Fast Flooding with Cooperative Transmissions*, where nodes combine signals from different senders at the Physical layer, claiming that the flooding time scales only logarithmically with the network size. The results show that this technique delivers data faster than conventional flooding. The authors suggest no constraint on the physical scope of flooding, which can congest the network. Furthermore, the protocol was designed for broadcast, which does not correspond to the IWSN paradigm of convergecast.

Single Gossiping with Directional Flooding (SGDF) [42] defines an initialization phase aimed at setting up *gradients* from the sink to the every node in the network. Gradient is equivalent to hop count, it tells about the distance to the sink and is used to find the shortest path. The sink broadcasts a *hello* message containing a *threshold* value and the gradient set to 1. Nodes receive this message, save the threshold and examine the gradient. A node receiving a hello message compares the gradient value in the message with its own. If the former is smaller, new gradient is being saved, the gradient value in hello message is incremented and it is forwarded further; otherwise, the hello message is discarded. The data source combines elements of gossiping and flooding in order to propagate the information. First it determines the set of potential next-hop nodes using a directional flooding criterion, and chooses the next hop in the gossip-like way. Namely, source polls its neighbors prior to transmission, and randomly selects the next hop among the neighbors with smaller gradient. If no neighbors have a smaller gradient, one with equal gradient is randomly selected. Otherwise, source randomly chooses any neighbor for next hop. The non-selected nodes generate a random value and compare it with previously mentioned threshold. If the generated value is smaller than threshold, the node enters *directional flooding mode*, where it forwards the data only to the neighbors with smaller gradient. By varying the threshold value from 0 to 1, SGDF can be scaled from pure gossiping to directional flooding. This implies a trade-off between small overhead of gossiping and high delivery ratio of directional flooding. If $p(i)$ and $R(i)$ are packet overhead and packet delivery ratio, for threshold i, respectively, then for the given distribution of weighting factor x, the optimal threshold T_h is:

$$T_h = x\frac{R(1.0) - R(i)}{R(1.0) - R(0)} + (1 - x)\frac{p(i) - p(0)}{p(1.0) - p(0)} \quad (2)$$

A potential drawback is that hello message can go too far in one round of hops due to varying channel conditions, providing a too optimistic hop distance. The results of simulations show that SGDF exhibits slightly higher delay than flooding, for value of x between 0.4 and 0.6. This protocol is inadequate for industrial control applications due to its complexity and increased latency, caused by polling.

Farivar *et al.* propose *Directed Flooding* [11], where nodes are allowed to rebroadcast only if they are located inside the directional virtual aperture of the sender, concentrated around the straight line that connects source and the sink.

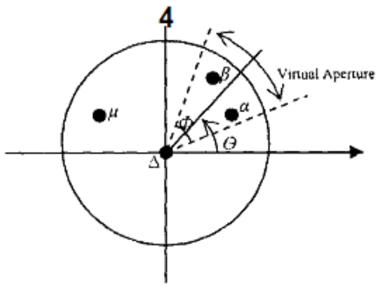


Figure 3: θ - transmission virtual aperture of the node Δ

In Figure 3, nodes α and β are in the transmission aperture of node Δ, whose initial size is ϕ. Aperture size θ can be chosen as:

$$\theta = n\phi \pm \frac{\phi}{2}, n = 0, \pm 1 \pm 2, ...; |\theta| \leq \pi \quad (3)$$

Every neighboring node can determine by itself whether it is inside the aperture using the following criterion and information about sender coordinates and aperture size:

$$\theta - \frac{\phi}{2} \leq \arctan(\frac{X_{current} - X_{previous}}{Y_{current} - Y_{previous}}) \leq \theta + \frac{\phi}{2} \quad (4)$$

If the condition is satisfied, node retransmits the packet and waits for acknowledgments. If it does not receive any, it rotates the aperture clockwise by a predefined angle. The process repeats, and if still no acknowledgments arrive, the aperture is mirrored around angle θ=0. Duplicated packets are discarded. A shortcoming of this protocol are the retransmissions, which, as previously mentioned, are an undesired feature in real-time data dissemination.

Directed Flooding with Self-Pruning [12] is an enhancement of Directed flooding. This approach further reduces flooding redundancy by introducing additional criteria for rebroadcast. Namely, a node checks whether the packet was retransmitted before, whether it is outdated, and whether there exists sufficient energy for retransmission. If the packet passes all these checks, a random *assessment delay* is introduced, during which, if no acknowledgments for the packet are heard, packet ultimately gets resent. Purposely increasing the delay in a time-critical application such as wireless industrial control is far from desired.

2.3.2 Stateless Weight Routing

Soyturk and Altilar [35] propose a concept of *weights* in the routing process. They suggest that a node's weight can be calculated from node's position (relative to the sink), and parameters such as link quality between the current and the potential next hop or current traffic conditions and congestion. Every intermediate node inserts its own weight and destination's weight into the packet (weight of the sink is zero) and broadcasts it. The receiving node compares these values with its own weight and decides whether to rebroadcast or drop the packet. The goal is to forward the packet towards the node with a smaller weight than sender's, whereas the sink is assigned the weight equal to zero. The weight of node k is:

$$w_k = f_{location}(k) + f_{link}(k) + f_{traffic}(k) \tag{5}$$

This approach gives the possibility of optimizing on certain network parameters, by including them into the weight formula. The second term of the equation refers to the node-specific parameters, such as Link Quality Indicator between the current and the potential next hop. The third term can include network parameters, such as current traffic conditions and available space in node buffers. Additionally, a threshold can be introduced to create the minimum value of the weight difference that will be sufficient for broadcast. This way, the number of retransmitters is reduced - the nodes closer to the sender have smaller chances of being chosen for rebroadcast and only the biggest contributors will be allowed to retransmit.

2.4 Conclusions of State-Of-The-Art literature study

The presented approaches refer to conventional WSNs and, as such, are inadequate for IWSN applications for several reasons:

- *Network size:* as previously mentioned, ordinary WSNs can contain up to several hundreds and thousands of nodes, while IWSNs are most often limited to tens of nodes. The majority of routing protocols mentioned in this section are designed for conventional WSNs and some of the directed flooding/gossiping protocols have very sophisticated flood direction/next hop selection mechanisms whose consequent benefits could not come to the fore in a small sensor population such as IWSN. Industrial WSN deployments are usually 2- or 3- hop networks.

- *Randomness:* randomness in the forwarding decision-making is unacceptable, because industrial control applications require deterministic latency and reliable delivery.

- *Coverage:* almost all of the presented flooding-based solutions aim at coverage, rather than convergecast, which is the case with IWSN.

Only certain aspects of the solutions presented above are utilizable for IWSN applications. In particular, the location-based concept of SWR and threshold-based principle are used in defining the proposed solution. The extracted value of the literature study has to do with the ways to reduce and control flooding traffic, as well as location-based forwarding criteria.

3 THE PROPOSED LIGHTWEIGHT SOLUTION

3.1 Properties of the proposed flooding-based approach

The proposed lightweight solution has virtually no control message exchange nor routing infrastructure, in order to minimize the traffic overhead and increase the efficiency of traffic resources. Furthermore, there is no heavy burden of path recalculation triggered by link failures. Algorithm of the proposed solution is shown below, preceded by its formal description. The key features of the proposed solution are:

- **A distributed routing algorithm:** each intermediate node independently decides whether to retransmit or discard the received packet. All the information necessary for making the forwarding decision is extracted or derived from the content of data packets.

- **Location-based protocol:** it is assumed that nodes are aware of their physical whereabouts and are able to compute their own distance to the sink d_k. If we define (x_k, y_k, z_k) as the Cartesian coordinates of the node k, its distance to the sink is:

$$d_k = f_{location}(k) = (x_k - x_{sink})^2 + (y_k - y_{sink})^2 + (z_k - z_{sink})^2 \tag{6}$$

  As previously stated, node placement in IWSN is deterministic and fixed, so there is no need to implement complex positioning algorithms. The position can be determined externally (by the operator) and downloaded into the node's memory. Each packet contains the coordinates of its previous hop, and this information is used in order to provide constant advancement towards the sink. The position of the sink is adopted as the center of the Cartesian coordinate system, and all coordinates are defined with respect to this point.

- **Duplicate packet handling:** every transmitted packet contains an (i, s) pair, where i stands for the source node address and s is the unique application payload identifier, called the *sequence number*. The i parameter unambiguously identifies the originating node, while s is unique for every piece of data sent by that node. Every node should manage a container to store (i, s) pairs of seen packets. Upon reception of a packet, its (i, s) pair is extracted and examined. If the packet was received before, it is discarded.

- **Handling of outdated packets:** a deadline equal to the sensor refresh rate is introduced. Each node compares the age of incoming packet with the deadline, and if the packet is outdated, it is discarded. This feature is introduced in order to free up traffic resources from old packets. The packet generation time is inserted into every piece of data at the generating node, so it is available to every recipient of the packet in question.
- **TTL limitation:** IWSN deployments consist of several dozens of nodes. The outliers in IWSNs are usually not more than 3 hops away from the sink and the TTL field of data packets should be set with respect to the network topology for two reasons; firstly, since the number of packets grows rapidly with each hop, network congestion will occur quite fast, unless packet lifetime is limited. Secondly, as previously mentioned, the IWSN sensor measurements get outdated after certain time, and delivery of outdated packets is meaningless. Hence, TTL value in the IP header is limited to 2 or 3.
- **Cross-layer support:** the considerations of this work are not fully confined to the Network layer and the routing protocol. In order to further enhance the performance of the proposed solution, a simple TDMA scheduling principle is utilized: the nodes that lie one hop away from the sink are assigned more timeslots for transmission, because they serve as both sources and forwarders of network traffic. This will be explained in more detail in Subsection 3.2.

3.2 TDMA scheduling support and mathematical constraint on maximum network size

The MAC layer protocol assumed in this work is TDMA with timeslot duration of $T_{slot} = 10$ ms, in order to converge to WirelessHART protocol stack. In TDMA networks, the time is divided into slots, and only one node may transmit during one particular slot. The number of receiving nodes during a timeslot is arbitrary. In conventional battery-powered WSNs, nodes go to idle state for as long as possible and are activated only when they are scheduled for listening/transmitting. IWSNs do not have this constraint, so the number of listening nodes within a timeslot is not limited.

The timeslots are grouped into *superframes*. We assume that TDMA networks operate in cycles and duration of a cycle is equal to the superframe duration - during one cycle, each sensor reports its measurement at least once. A certain number of nodes is placed more than one hop away from the sink, which they can reach via a number of forwarding nodes. One of the evaluation criteria (which will be defined in Subsection 4.5) imposes a deadline on the end-to-end delay, meaning that all the packets with end-to-end delay larger than sensor refresh rate are deemed as outdated. This constraint is shown below and the values involved stand for end-to-end delay T_{e2e} and sensor refresh rate T_{cbr}, respectively:

$$T_{e2e} \leq T_{cbr} \tag{7}$$

The following assumptions hold for the considerations below:

- Networks with maximum two hops in radius are considered: the outliers are at most two hops away from the sink.
- All sensors have equal refresh rates - they send out measurements at equal intervals.

Since the duration of one superframe equals the duration of one cycle (in which every node will send its reading to the sink at least once), the following condition must be fulfilled as well:

$$T_{cbr} \geq T_{superframe} = T_{slot} \times n_{slots} \tag{8}$$

In the above inequality, n_{slots} is the total number of slots in one superframe. The timeslots are delegated to particular nodes and each node must have at least one guaranteed timeslot. The nodes in the first tier (i.e. nodes that are one hop away from the sink) must be assigned additional timeslots, because they must deliver their own reading and forward readings of their neighbors in the second tier. The number of additional slots is equal to the number of second-tier neighbors that fulfill the forwarding conditions, defined in Subsection 3.3. Finally, if we define the following variables: n_{nodes} - the number of nodes in the network; n_{1st}, n_{2nd} - the number of nodes in the first and second tier, respectively; x_i - the number of first-tier neighbors of a second-tier node i, whose forwarding conditions are fulfilled by node i, then the following condition must be satisfied:

$$n_{slots} = \frac{T_{cbr}}{T_{slot}} \geq n_{nodes} + \sum_{i,2ndtier} x_i \tag{9}$$

This is equivalent to:

$$n_{nodes} \leq \frac{T_{cbr}}{T_{slot}} - \sum_{i,2ndtier} x_i \tag{10}$$

In other words, the maximum number of nodes that a network can serve (under the previously defined assumptions), depends on the sensor refresh rate, timeslot duration and the number of forwarders for all second-tier nodes. The summation in equation 10 equals the sum of first-tier forwarders for all second-tier nodes i.e. the total number of timeslots within one cycle that must be allocated for forwarding.

Previous considerations are related to the total number of nodes that can be scheduled for the given number of slots (i.e. given T_{cbr}). Another issue is the order of transmissions, whereas in this work a simple algorithm is applied: first-tier nodes are first given channel access (i.e. granted permission to transmit), in the clockwise direction, starting from an arbitrary first-tier node. After all first-tier nodes have transmitted, the slots are assigned to the second-tier nodes, whereas each second-tier node transmission is followed by m_i slots, where m_i is the number of first-tier neighbors of node i. This way, an immediate delivery of data from the second tier to the sink is accomplished. The order of transmissions during one cycle for the network from Figure 11, is shown in Figure 4.

Slot	1	2	3	4	5
Event	10->Sink	20->Sink	12->Sink	21->Sink	22->Sink
Slot	6	7	8	9	10
Event	4->Sink	19->Sink	23->Sink	13->Sink	27->Sink
Slot	11	12	13	14	15
Event	17->Sink	28->Sink	8->Sink	18->20	20->Sink
Slot	16	17	18	19	20
Event	16->21, 22	21->Sink	22->Sink	5->19, 23	19->Sink
Slot	21	22	23	24	25
Event	23->Sink	14->27, 17	27->Sink	17->Sink	Sink->All

Figure 4: Sequence of transmissions for the network in Figure 11

3.3 The forwarding criteria

Whether or not a received packet will be rebroadcast depends solely on the five forwarding conditions, which all must hold in order for the retransmission to take place. The pseudocode of the proposed approach is shown below, followed by the definition of all five forwarding conditions.

Algorithm 2 The proposed solution

Receive a packet (i, s)
if $(C_1 \wedge C_2 \wedge C_3 \wedge C_4 \wedge C_5 = TRUE)$ **then**
  insert (i, s) in table
  $forward(i, s)$
else
  $discard(i, s)$
end if
Go to waiting mode

Condition C_1 states that a received packet will be considered for forwarding if its age T_{age} is not more than the refresh rate T_{cbr} of its originating sensor:

$$T_{age} \leq T_{cbr} \tag{11}$$

The justification of this condition is related to one of the two evaluation criteria presented in Subsection 4.5.

Condition C_2 holds true for an (i, s) pair if the output of function $unseen(i, s)$ is logical TRUE, i.e. if a pair (i, s) does not already exist in the container of seen (i, s) pairs:

$$C_2 = unseen(i, s) \tag{12}$$

Nodes have limited memory resources, and the table of seen packets can grow very large. Therefore, in a real-world implementation, each entry should be flushed after time T_{cbr}, in order to economize memory. After this time, the arrival of a packet whose entry has been already flushed will be handled by Condition C_1, i.e. it will be discarded, because it will be older than T_{cbr}.

Condition C_3 allows a packet to be considered for forwarding only if its previous hop is a node that lays farther from the sink than the current node, i.e. if:

$$d_{previous} > d_{current} \tag{13}$$

This condition provides constant advancement of a packet towards the sink. The distance from the sink d is defined in Subsection 3.1.

Condition C_4 holds true if the previous hop of the packet was a node located more than one hop away from the sink, i.e. the nodes that have the sink within their range do not need forwarding support.

Condition C_5 implies that if $d(previous, current)$ is the mutual distance between the previous and current hop, the packet can be forwarded only if this distance is smaller than the adopted value of *threshold*:

$$d(previous, current) < threshold \tag{14}$$

The value of *threshold* is a parameter proprietary to each forwarding node, which will consider a packet for forwarding only if it comes from a node that is less than *threshold* meters away. By varying this value, a node can reduce or increase the number of neighbors whose packets it considers for forwarding (all five conditions must hold for the forwarding to occur). Every node k has a number of neighbors. If we label as *friends* all the neighbors which, from the perspective of node k, fulfill conditions C_3, C_4 and C_5, then the number of TDMA timeslots that will be assigned to node k must be equal to the number of its *friends*, incremented by one. As previously explained in Subsection 3.2, this is because node k must transmit its own data and forward the data from all of its *friends*, which should be supported by an appropriate number of dedicated timeslots.

This, somewhat contradictory condition C_5, can be motivated as follows. The proposed approach, albeit being lightweight, is built upon a location-based hierarchy, in conjunction with scheduling. The existence of five forwarding conditions makes it possible to limit the number of forwarders, and, for a given value of *threshold*, the number of forwarders is deterministic. In other words, the number of *friends* of a given node is fixed and it can be changed only by modifying the forwarding criteria. In order for the deadlines to be met and to avoid network congestion, the output buffers in the forwarding nodes must perform as sustainably leaky buckets, meaning that their output buffer queues must not grow over time. This is possible only if a forwarder has been assigned enough slots in order to serve all nodes that, from its own perspective, fulfill all five forwarding conditions. Rayleigh fading can cause both extension and contraction of the transmission range. If we consider a network without condition C_5, then, due to Rayleigh fading, a packet can reach too far in one hop and end up at a node which does not have enough slots to serve all nodes that, from its own perspective, fulfill the four conditions. This will trigger a domino effect, i.e. piling up of packets in queues, network congestion and deadline misses. Therefore, condition C_5 will prevent this by maintaining the balance between the number of packets that should be forwarded within one cycle and the number of available timeslots. This is the rationale behind the decision to discard the packets that come from too far away. The IWSN topology is deterministic and fixed, and the value of *threshold* should be downloaded to all the nodes in the initialization phase and adjusted in accordance with network conditions.

4 SIMULATION SETUP

The proposed flooding-based algorithm is evaluated by using the *QualNet 5.0* discrete event network simulator. Additionally, it is compared to a number of ad-hoc WSN routing protocols that already exist in QualNet library. This comparison has an illustrative purpose for Scenarios A-D, whereas the only relevant benchmarks in these setups are the evaluation criteria defined in Subsection 4.5. However, the performance of the proposed approach relative to other routing protocols is relevant in Scenarios E and F.

4.1 Simulation parameters

The simulations are executed on a WirelessHART-like protocol stack, with all the relevant WirelessHART features retained, hopefully without a loss of generality. The protocol stack is shown in Table 2, composed with the intention to converge to the actual protocol stack of WirelessHART, subject to availability of models in QualNet protocol library. This work is a proof of concept, and it is not necessary to entirely replicate the WirelessHART protocol stack. However, using TDMA on the MAC layer is essential, due to the considerable influence of scheduling on latency. The nodes are placed within a 100 x 100 m area, with a centrally located sink node. This is feasible in practice, because, although there exists zero degrees of freedom in node placement, sinks can be freely positioned in any number. During the simulation, the nodes are instructed to periodically send measurements to the sink. The most important features of every layer in the simulation are explained below.

- **Propagation environment:** A common setting for IWSNs is a spacious production hall, with plenty of metallic surfaces, constant object movement, and, quite often, non-line-of-sight communication between the sensor nodes. The parameters of wireless channel dynamics are selected in order to emulate the realistic setting as much as possible:
  - **Pathloss model:** *Street Microcell model* [36], which calculates the path-loss between transmitter-receiver pairs that are located in adjacent streets in an urban canyon. The essential difference between pathloss models in QualNet is the achievable transmission range. In particular, Street Microcell model allows the range of roughly 50 m for output power of 10 dBm. Any other

pathloss model could have achieved this range with appropriate scaling of output power. Since output power in WirelessHART is limited between -10 and 10 dBm, a pathloss model that achieves transmission range relevant to the network size is chosen.

  - **Shadowing model:** *Lognormal shadowing model* [32], which uses a lognormal distribution for the shadowing value. It represents the slow variations of received signal power against the distance between transmitter and receiver.
  - **Fading model:** *Rayleigh fading model* [33], which is a statistical model to represent the fast variation of signal amplitude at the receiver. In wireless communications, Rayleigh fading models the situation when there is no line of sight between the transmitter and receiver, which is quite often the case in realistic scenarios.

- **Physical layer:** The IEEE 802.15.4 Physical layer model is part of WirelessHART stack. This model and TDMA MAC layer model in QualNet library are not compatible. Hence, the *Abstract model* is used on the Physical layer. This is a generic PHY model which can be used to simulate different Physical layers and it is modulation-agnostic. Abstract model simulates a Physical layer that is capable of carrier sensing and is able to work with both *BER-based* and *SNR threshold-based* reception models. The PHY Abstract model does not refer to any particular type of modulation. However, the BER-based reception model requires user-generated BER tables. This gives way to emulating the desired Physical layer by obtaining the tables for the desired type of modulation and all the adherent Physical layer parameters. In the simulations, SNR-based reception model is used, with WirelessHART-compatible reception threshold and receiver sensitivity (-85 and -95 dBm, respectively). The antennas used are omnidirectional.

- **MAC layer:** QualNet TDMA MAC layer model is used, with the timeslot duration set to (WirelessHART-compatible) 10 ms. The superframe duration depends on the number of nodes and their constellation, as previously described. The exact scheduling sequence is defined in a separate .tdma file.

- **Network layer:** Network layer is IP-based, which is not a feature of WirelessHART. IP is chosen in order to facilitate the implementation, since it provides an addressing scheme. The routing protocols used for comparison with the proposed approach will differ between scenarios.

- **Transport layer:** UDP protocol is used on the Transport layer. UDP is preferred over TCP because delivery of a new process measurement is more sensible than the retransmission of an old one, as previously explained in Subsection 1.3.

- **Application layer:** The process sampling and delivery of sensor readings are modeled by a Constant Bit Rate (CBR) application. The sensor refresh rate depends on a scenario, and is varied between 250 ms and 1000 ms. The payload of the application is 32 bytes. Every packet generated by the CBR application has a unique identifier, called the *sequence number*. This parameter, together with the source address (added at the network layer) uniquely identifies every packet in the network. This feature is exploited in order to reduce the flooding traffic by discarding already seen packets.

Table 2: The summary of simulation parameters

Simulation parameters		
Layer	**Parameter**	**Value**
Physical	Physical layer model	Abstract PHY
	Reception model	SNR-based
	Data rate	250 kbps
	Output power	10 dBm
	Frequency	2.4 GHz
	Antenna type	Omnidirectional
	Channel Model	Street Microcell model [36]
	Shadowing Model	Lognormal
	Fading Model	Rayleigh fading
	Mean transmission range	50 m
MAC	Timeslot duration	10 ms
	Superframe duration	Depends on the number of nodes
Network	Network protocol	IP
	Routing protocol	The proposed solution
Transport	Transport protocol	UDP
Application	Payload size	32 bytes
	Refresh rate	250-1000 ms

4.2 Implementation

QualNet simulator is written in C language. The implementation of the proposed routing protocol included writing a C program that performs the testing of a packet against the five forwarding criteria, as well as incorporating it into the QualNet hierarchy. The integration of the new protocol was conducted by following the steps suggested by QualNet 5.0 Programmers Guide [2]. For the purpose of debugging and collection of statistics, the reserved word *printf*of the C language was extensively exploited.

4.3 Simulation scenarios

The performance of the proposed algorithm and several routing protocols is tested in a number of different scenarios, each with the purpose of assessing a different performance aspect. All the results presented for the proposed approach are obtained while simultaneously satisfying both evaluation criteria defined in Subsection 4.5.

- **Scenario A: Average end-to-end delay evaluation.** The setups from Figure 11 and Figure 12 were simulated under fading-free propagation conditions, in order to isolate the problem and focus on generic speed-comparison of the protocols. The nodes have a refresh rate of $T_{cbr} = 250$ ms and the measurable of interest in this scenario is end-to-end delay T_{e2e}.

- **Scenario B: Robustness to node failure.** Conventional routing protocols react to link failures via recovery mechanisms that include route recalculation. This can be a time-consuming process. In this scenario, the node 13 in Figure 13 is shut down at a certain time-point in the simulation, in order to assess the recovery speed of the evaluated protocol. The speed of recovery is evaluated by observing the packet delivery ratio and the time necessary to establish a new route.

- **Scenario C: Robustness to severe channel conditions.** The scenarios from Figure 14, 15 and 16 are exposed to Rayleigh fading and the corresponding latencies and PDRs are observed. The Rayleigh fading model used is defined in Subsection 4.1.

- **Scenario D: Maximum feasible node populations.** The goal of this scenario is to investigate the maximum acceptable network sizes, with respect to evaluation criteria defined in Subsection 4.5. The assumption is that 75% of the nodes should be in the first tier and 25% in the second. Furthermore, the topologies are composed in such a way that nodes located 2 hops away from the sink have two neighbors within range.

- **Scenario E: Complexity comparison.** There are two types of events in QualNet: *packet events* and *timer events.* Packet events represent exchange of data packets between layers or nodes. Packet events also model the communication between different entities at the same layer. Actions at Network layer trigger a number of operations at other layers of the node as well as in other nodes in the network. These operations translate into operations in hardware or network traffic. In this setup, the complexity of the proposed approach is estimated by observing the number of operations executed in the network and a comparison to other WSN routing protocols is made. Since the numbers as such are not illustrative, they are normalized by the number of events in the scenario when flooding-based approach is used and compared with corresponding observables of other routing protocols examined. The number of operations on the Network layer alone could have been observed, but since the events on Network layer trigger operations on all layers it is more sensible to observe the overall number of operations and events in the network.

- **Scenario F: Energy consumption.** One drawback of flooding frequently encountered in the literature is resource blindness, defined in Subsection 2.2. One aspect of resource blindness in flooding is the excessive energy consumption. Energy consumption at each node is estimated using the Generic battery model from QualNet Wireless Model Library, and it is observed for the proposed solution and several other WSN routing protocols for Transmit, Receive and Idle modes. For comparison purposes, the results shown on the figures are normalized with respect to energy consumption of the proposed solution.

4.4 The influence of Rayleigh fading and SNR-based reception model

The quantification of Rayleigh fading is shown in Figure 5. This graph is obtained by measuring the PDR of a point-to-point transmission after placing two sensor nodes at different distances. Rayleigh fading is implemented following the references of [32]. For each packet received, the fading attenuation is obtained using a table lookup indexed by time. The lookup table contains a long trace of zero mean, unit variance Gaussian distributed in-phase and quadrature components.

The use of SNR-based reception model at the Physical layer implies that a whole packet is lost if its RSS does not exceed the reception threshold. This mechanism emulates slow Rayleigh fading, where entire packets are lost. In the simulations, the RSS fluctuates in the range between -57 ÷ - 84 dBm, which is similar to the values experienced in a real-life case study presented in [5].

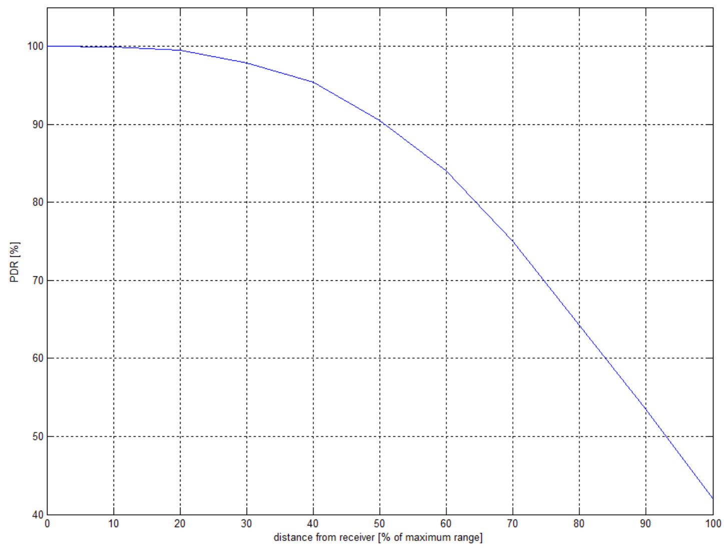


Figure 5: Dependency of PDR on Rayleigh fading model used

4.5 Evaluation criteria

IWSN should deliver sensor readings within the predefined time-frames and with a high level of reliability. The performance in Scenarios A-D is evaluated via two distinct observables:

- *End-to-end delay*, defined as the time that a packet spends traveling between the Application layers of the sending node and the sink. It mainly consists of queuing time in the buffers of intermediate nodes, and, to a lesser extent, of the processing time in the nodes along the route to sink.
- *Packet delivery ratio*, which is the quotient of the cumulate number of packets sent by Application layers of all the nodes in the network, and the number of packets received in the sink during the simulation. The proposed solution provides delivery of multiple instances of the same packet to the sink, but each packet will be counted exactly once i.e. the time of arrival of the first copy is considered in calculation of average end-to-end delay.

These observables are crucial in time-critical applications, it is possible to measure them in QualNet and they will be used as input for the following evaluation criteria of interest:

Latency requirement: real-time data delivery is of vital importance in IWSNs. In this model, the sensing devices transmit measurements to the sink at regular intervals. Sensor measurements in process automation have very limited time-validity. Therefore, it is essential that the sink is aware of a particular process sample before a new one is made. The evaluation criterion in this case translates to $T_{e2e} \leq T_{cbr}$, where the variables compared stand for end-to-end delay T_{e2e} and sensor refresh rate T_{cbr}, respectively. Non-compliance with this rule leads to deadline misses and unnecessary occupation of network resources, which can eventually lead to congestion.

Delay-limited capacity: this evaluation criterion combines capacity and outage probability and is expressed in the form of (m, k)-firm deadlines ([16, 17]), where the loss of at most m out of k consecutive packets is deemed acceptable. In this work, the values of $m = 2$ and $k = 3$ are adopted. In layman terms, this means that a loss of three or more subsequent packets is a showstopper.

4.6 Delimitations and assumptions

Network topologies with maximum of two hops and equal sampling rate for all sensors are assumed. The three-hop network case can be derived, and it will reduce the maximum number of nodes in the network, because a packet from a third-tier requires more forwarders, so more slots will have to be allocated for forwarding, in order to achieve a timely delivery.

Assessment of the proposed solution against the two evaluation criteria is of the uttermost importance in this Thesis, whereas the comparison with the selected benchmark ad-hoc WSN protocols has an illustrative purpose for Scenarios A-D.

TDMA is chosen as the medium access technique, in accordance with the Data Link layer specification of WirelessHART. Although this technique is usually avoided by authors, it provides deterministic performance in terms of average end-to-end delay and removes the possibility of packet collisions, which makes it suitable for IWSN applications.

5 SIMULATION RESULTS

All results obtained for the proposed flooding-based solution implicitly satisfy the two evaluation criteria defined in Subsection 4.5. In particular, all packets whose travel time is used in calculation of average end-to-end delay and packet delivery ratio have arrived to sink within the deadline and with the desired degree of reliability. This is the reason why end-to-end delay is quantified through its average value, and not through its distribution or confidence intervals - outdated packets are discarded on-the-fly in the intermediate nodes and do not participate in collection of final statistics. Since multiple copies of a packet may arrive to the sink, only the arrival time of the first copy is taken into consideration. The simulation time is 300 seconds for every scenario, whereas the number of sent packets depends on sensor refresh rate T_{cbr}, as shown in Table 3.

Table 3: The number of sent packets by every node for different values of T_{cbr}

Refresh rate	**Number of packets sent per node**
0.25 sec	1196
0.5 sec	598
0.75 sec	399
1 sec	299

5.1 Scenario A: Average end-to-end delay evaluation

Average end-to-end delays are measured in the 17-node network from Figure 11 and the 33-node network from Figure 12. Apart from the proposed approach, the following routing protocols are considered: AODV [31], DSR [23], DYMO [9], LAR1 [24], ZRP [15], STAR [27] and OLSRv2Niigata [10].

The underlying MAC protocol is TDMA, with the scheduling that allows the maximum number of nodes to be included in the network for the given sensor refresh rates (250 ms and 500 ms). In other words, traffic load is pushed to the upper bound for congestion-free network operation, in accordance with the considerations from Subsection 3.2.

The measured average end-to-end delays and packet delivery ratios presented in Table 4 clearly indicate that, with the exception of the proposed solution, none of the examined protocols can cope with this amount of traffic load and satisfy the evaluation criteria from Subsection 4.5. The average end-to-end delays for the proposed solution are 64% below the deadline, while other routing protocols perform poorly, with average end-to-end delays significantly above the deadline.

The results for Scenario A1 and A2 are presented for 8 and 4 different routing protocols, respectively. The reason is that only 4 routing protocols could cope with the population size and refresh rate of Scenario A2.

Table 4: Average end-to-end delays and PDRs for fading-free scenarios

Routing protocol	Scenario	Refresh rate	Average end-to-end delay	PDR
Proposed solution	A1	0.25 sec	0.091 sec	100%
AODV	A1	0.25 sec	7.178 sec	97.46%
DYMO	A1	0.25 sec	6.623 sec	97.32%
DSR	A1	0.25 sec	9.402 sec	96.38%
ZRP	A1	0.25 sec	49.403 sec	67.3%
LAR1	A1	0.25 sec	4.352 sec	98.58%
OLSRv2 Niigata	A1	0.25 sec	17.458 sec	87.35%
STAR	A1	0.25 sec	11.412 sec	92.38%
Proposed solution	A2	0.5 sec	0.168 sec	100%
AODV	A2	0.5 sec	95.477 sec	63.65%
DYMO	A2	0.5 sec	63.014 sec	72.87%
DSR	A2	0.5 sec	32.986 sec	83.95%

5.2 Scenario B: Robustness to node failure

In this scenario, node 5 from Figure 13 loses one of its neighbors, namely node 13. The proposed approach exploits two paths in parallel to deliver data from node 5 to the sink (via nodes 13 and 15), and the failure of one path will not cause interruptions in data delivery. Conventional routing protocols using node 13 to deliver data from node 5 will take certain time to recalculate the routing paths and shift them to node 15. This affects the number of packets delivered within the expected time-frame and overall latency. From the perspective of a unicast routing protocol, this is a trivial scenario, because the failing node 5 has only two neighbors, and the procedure of establishing a new path should be quite straightforward, compared to the situation when there are many neighbors to choose from.

The PDRs are presented in Figure 6 and values of *recovery time*, defined as the time between a node failure and reestablishment of the route via an alternative path, are shown in Table 5. The proposed approach exhibits 100% PDR, whereas its closest follower, Bellman Ford routing, delivers around 97% of packets and other protocols lagging behind by roughly 10%. The node failure scenario has shown that flooding adjusts smoothly to node failure, without any transitional periods. This does not hold for other protocols examined.

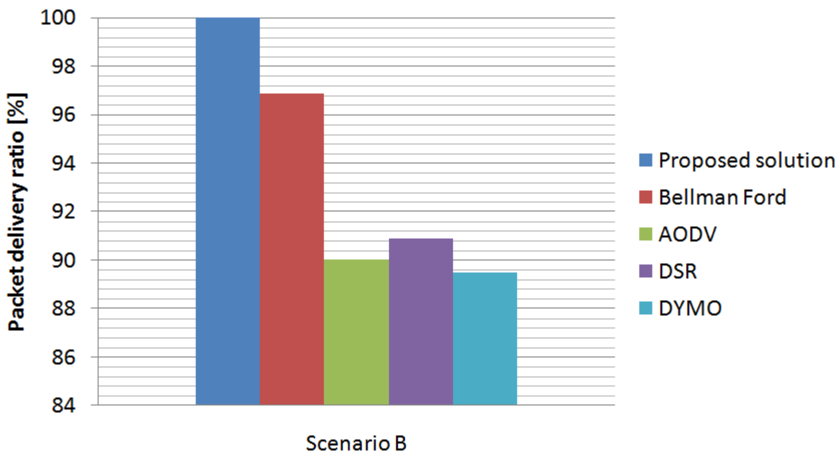


Figure 6: Packet delivery ratios for Scenario B (node failure)

Table 5: Recovery times for node failure scenario

Routing protocol	**Recovery time**
Proposed solution	0 sec
Bellman Ford	113 sec
AODV	$\geq$ simulation time
DSR	297 sec
DYMO	305 sec

5.3 Scenario C: Robustness to severe channel conditions

The networks from Figures 14, 15 and 16 with 16, 33 and 50 nodes and refresh rates of 250, 500 and 750 ms, are exposed to Rayleigh fading. The proposed solution has proven to be superior in terms of robustness to Rayleigh fading, compared to other protocols examined, exhibiting almost identical average end-to-end delay as in the case of fading-free scenarios, while the packet delivery ratio drops to around 80%, regardless of the network size. A common feature of Scenarios C1, C2 and C3 is the fact that second-tier nodes have two first-tier neighbors. Similarly to Scenario A, the networks comprise the maximum number of nodes that can support their respective refresh rates.

The results show that performance of other routing protocols deteriorates significantly with the increase of network size and is far from satisfying the timing and reliability constraints. Similarly to Scenario B, the good PDR of the proposed solution stems from the multipath data delivery. The results are presented in Table 6.

Table 6: Average end-to-end delays and PDRs for different scenarios under Rayleigh fading

Routing protocol	Scenario	Refresh rate	Average end-to-end delay	PDR
Proposed solution	C1	0.25 sec	0.088 sec	83.64%
AODV	C1	0.25 sec	12.290 sec	71.38%
DYMO	C1	0.25 sec	9.650 sec	71.47%
DSR	C1	0.25 sec	7.675 sec	69.28%
ZRP	C1	0.25 sec	51.228 sec	44.38%
LAR1	C1	0.25 sec	12.234 sec	70.53%
OLSRv2 Niigata	C1	0.25 sec	20.251 sec	55.86%
STAR	C1	0.25 sec	18.518 sec	27.50%
Proposed solution	C2	0.5 sec	0.183 sec	82.25%
AODV	C2	0.5 sec	130.390 sec	36.40%
DYMO	C2	0.5 sec	64.570 sec	55.28%
DSR	C2	0.5 sec	40.651 sec	63.27%
LAR1	C2	0.5 sec	3.576 sec	11.98%
Proposed solution	C3	0.75 sec	0.366 sec	81.95%
DYMO	C3	0.75 sec	75.820 sec	11.27%
DSR	C3	0.75 sec	120.940 sec	37.75%
IERP	C3	0.75 sec	47.580 sec	46.20%

5.4 Scenario D: Constraints in terms of node population size

The aim of this scenario is to investigate the feasible network sizes for the offered traffic load, with respect to the evaluation criteria from Subsection 4.5. Figure 7 shows the dependency of latency on network population size. The observed networks have a sensor refresh rate and deadline of $T_{cbr} = 1$ sec and 75% nodes located one hop away from the sink. According to the results, the proposed solution allows the use of larger networks than all other protocols, with respect to the latency constraint. AODV, DYMO and DSR can meet the demands of the two evaluation criteria only for networks of up to 20-25 nodes, whereas the average end-to-end delays exhibited by the flooding-based approach stay well below the deadline throughout the observed range of network sizes. The latency curve of the flooding-based approach has a constant slope, while the latencies of other routing protocols explode around the 18-node mark.

In order to assess the proposed solution in terms of feasible network sizes with respect to the evaluation criteria, the bounds of maximum node populations are investigated. The results in Table 7 illustrate the maximum node populations that can satisfy the $T_{e2e} \leq T_{cbr}$ and $(2,3)$-firm deadline criteria. These results are obtained under the following set of assumptions:

- Sensor refresh rates of 0.25, 0.5, 0.75 and 1 sec.
- 75% of nodes are located within one hop away from the sink.
- Second-tier nodes have exactly two first-tier neighbors.
- The networks satisfy the $T_{e2e} \leq T_{cbr}$ and $(2,3)$-firm deadline criteria

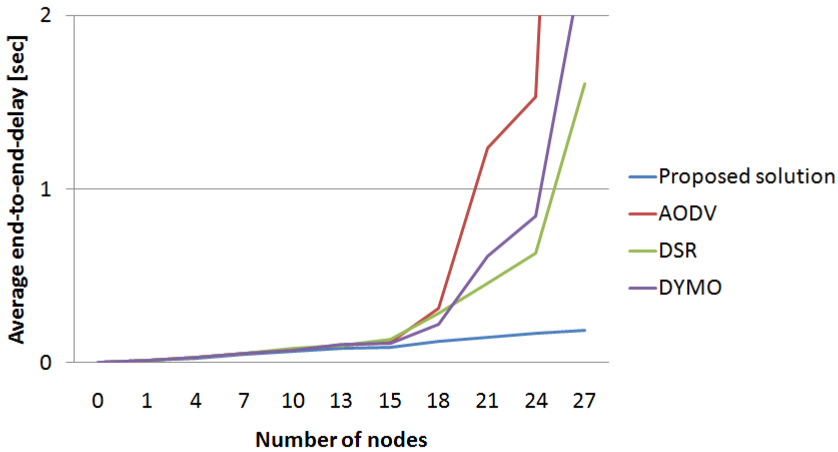


Figure 7: Average end-to-end delay as a function of network size

The numbers in Table 7 can be justified with the help of conclusions of Subsection 3.2. For example, for $T_{cbr} = 750$ ms, the following equalities hold:

$$n_{slots} = \frac{T_{cbr}}{T_{slot}} = \frac{750ms}{10ms} = 75 \qquad (15)$$

$$n_{slots} = n_{nodes} \times 0.75 + n_{nodes} \times 0.25 + 0.25 \times 2 \qquad (16)$$

$$n_{nodes} = \frac{n_{slots}}{0.75 + 0.25 + 2 \times 0.25} = \frac{75}{1.5} = 50 \qquad (17)$$

The first, second and third term in the Equation 16 refer to 75% of nodes in the first tier, 25% of nodes in the second tier and average number of first-tier forwarders for every second-tier node (two). Their sum equals the required number of timeslots in the superframe, in order to meet the latency constraint.

The feasible network sizes are sufficient for the majority of IWSN applications. The need for a larger network can be satisfied by deploying additional sinks, thus partitioning the overall node population into clusters. Furthermore, a number of routers, nodes that will not generate, but only forward the traffic, can be deployed.

Table 7: Maximum network sizes and average end-to-end delays for the proposed approach

Refresh rate	**Maximum network size**	**Average end-to-end delay**
0.25 sec	16 nodes	0.091 sec
0.5 sec	33 nodes	0.168 sec
0.75 sec	50 nodes	0.356 sec
1 sec	65 nodes	0.457 sec

5.5 Scenario E: Complexity comparison

The complexities of different routing protocols are observed on the network from Figure 14. As previously motivated, the number of intra-simulation events executed for each routing protocol is normalized by dividing with the corresponding observable in the case of the proposed solution. Although the complexity of routing protocols is compared, the observable is the total number of events in the network, rather than the number of events on the network layer. The reason for this is that actions of the Network layer trigger events on other layers. Hence, it is necessary to observe occurrences on all layers in order to make a fair comparison of complexities.

The results can be found in Table 8. According to the results, the increase in the total number of operations in the network with respect to other protocols is not more than 10%.

Table 8: Normalized number of events executed for various routing protocols

Routing protocol	**Scenario**	**Normalized number of events executed**
Proposed solution	C1	1.0000
AODV	C1	0.9296
DSR	C1	0.9324
DYMO	C1	0.9255
LAR1	C1	0.9192
STAR	C1	0.9736
ZRP	C1	0.9840

5.6 Scenario F: Energy consumption

The presented measurements of energy consumption are cumulative and normalized, i.e. the numbers refer to overall energy consumption in the network, which is normalized with respect to the consumption of the proposed flooding approach. The network of interest is shown on Figure 14.

Contrary to the widespread opinion, the proposed flooding-based approach has only a moderate increase of energy consumption of roughly 10%, with respect to the majority of other routing protocols compared. The proposed flooding approach consumes up to 15% more energy in Transmit and Receive mode compared to AODV, DSR, DYMO, OLSR and ZRP protocols and about 2.5% less energy than LAR1. In the idle mode, the flooding-based approach is an average consumer of energy among the routing protocols observed. The energy consumption ratios for the transmit, receive and idle mode are depicted below.

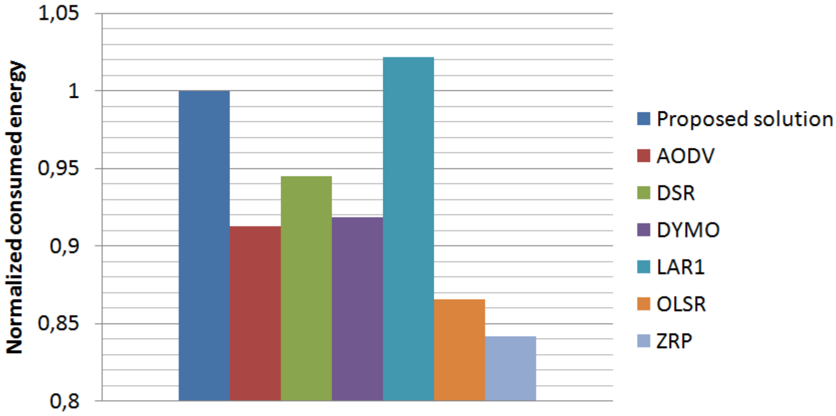


Figure 8: Normalized energy consumption in Transmit mode

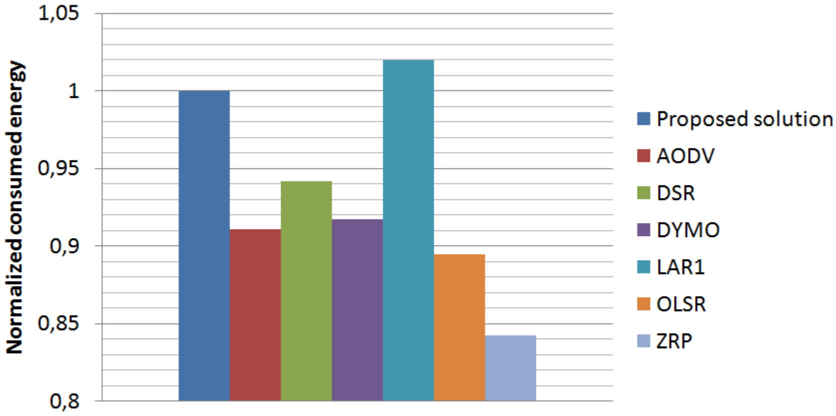


Figure 9: Normalized energy consumption in Receive mode

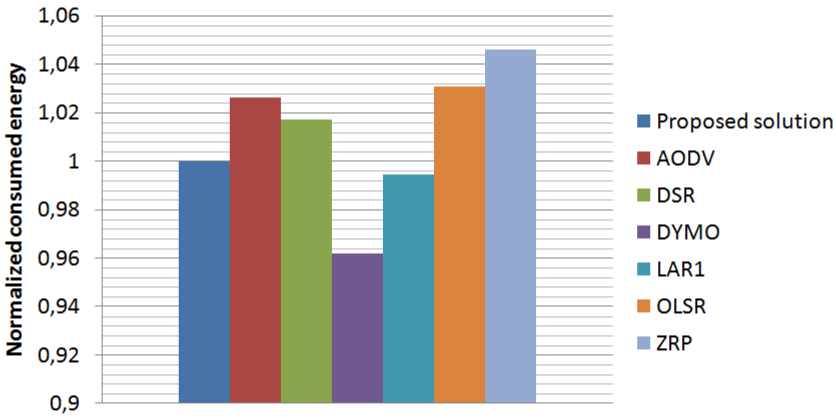


Figure 10: Normalized energy consumption in Idle mode

6 CONCLUSION

The aim of this work is to define a lightweight routing flooding-based routing protocol with properties required by wireless control applications and test it against the adequate evaluation criteria. The simulation results show that the proposed flooding-based solution can be efficiently used for this purpose under certain conditions and limitations. The most important drawback of flooding is the excessive amount of traffic that it creates and the consequent network congestion. Starting from the generic form of flooding, several modifications are introduced in order to reduce the traffic redundancy, while preserving the good properties of flooding, which were the initial motivation for considering it as a data dissemination technique in IWSN.

The use of TDMA provides greater control of the speed of data delivery and deterministic latency. However, due to timing and reliability constraints defined in Section 4.5, the number of slots in a superframe is limited and their allocation to particular nodes is the key factor in meeting these constraints. This is correlated to the node placement problem, where the number of neighbors of second-tier nodes determines the number of timeslots dedicated to forwarding. Since the node placement is deterministic and strictly defined by the customer, with insignificant degree of freedom, the term *neighbor* can be abstracted via the term *friend* and variable *threshold*, as explained in Subsection 3.3 and Subsection 4.6. The main conclusions are summarized below:

- The proposed routing protocol delivers data faster and more reliable than other protocols examined in both Rayleigh fading and fading-free conditions.
- Transition in the case of link or node failure is seamless and no additional time for recovery is necessary, the traffic flow is uninterrupted, albeit packet loss.
- The proposed approach does not exhibit a drastic increase neither in energy consumption nor complexity, compared to other protocols. The complexity is estimated via the number of events executed during the simulations.
- Feasible network sizes depend on node placement and particularly on the number of neighbors of nodes which lie more than one hop away from the sink.
- The only overhead of this protocol is sending of the node coordinates. The representation of coordinates requires roughly centimeter precision and this overhead

is in the order of several bytes. On solution is to transfer this burden to node memory, where the nodes could learn and map their neighbor's coordinates to the respective node ID's.

- In case of different refresh rates in the network, additional overhead of several bits is necessary: in order for the receiving node to assess the aging of the packet, the sender can use these bits to inform the potential forwarders about its refresh rate.

6.1 Future work

Further improvements should target increasing the feasible network sizes, as well as exploiting more of the information that is already available to the nodes. Some of the pointers for future development of the concept are:

- Exploitation of Channel State Information: utilizing the knowledge about one of the most important disruption factors in IWSN will results in better adaptivity of the network to the dynamic propagation conditions.
- Development of dynamic scheduling: scheduling is one of the key aspects of the proposed solution,
- Data aggregation: integrating the sensor readings from multiple nodes into a single packet will free up a number of timeslots within one superframe and increase the upper limit on network size.
- Incorporation of downlink: monitoring is just one of IWSN applications. In order to diversify the range of applications, downlink should be incorporated into the proposed solution, for delivery of commands to the actuators.

7 PUBLICATION

A Lightweight Routing Protocol for Industrial Wireless Sensor and Actuator Networks

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***Abstract*—The applications of Industrial Wireless Sensor and Actuator Networks are time-critical and information must be delivered within the predefined deadlines with a considerable deal of reliability. A notable shortcoming of the existing wireless industrial communication standards is the existence of overcomplicated routing protocols, whose adequacy for the intended applications is questionable [1]. This paper evaluates the potentials of flooding as a data dissemination technique in IWSANs. The concept of flooding is recycled by introducing minimal modifications to its generic form and compared with a number of existing WSN protocols, in a variety of scenarios. The simulation results of all scenarios observed show that our lightweight approach is able to meet stringent performance requirements for networks of considerable sizes. Furthermore, it is shown that this solution significantly outperforms a number of conventional WSN routing protocols in all categories of interest.**

I. Introduction

Industrial Wireless Sensor and Actuator Networks (IWSANs) for process automation are slowly replacing their wired counterparts, resulting in easier deployment, flexibility and cost reduction. According to [2], wiring and installation can make up to 90% of the device cost.

The *causa sui* of IWSANs is to report sensor readings and deliver actuator data in real time, in order to stabilize the unstable processes and maximize the production rate. The required latencies are application-specific, and range from the order of tens of milliseconds for e.g. pressure sensors, up to several seconds for temperature sensors [1]. Sadly, the advantages of wireless control have not been fully exploited. Park *et al.* [3] identify a dichotomy in the design of existing IWSANs, arguing that process engineers have authored the application software, while the communication engineers were responsible for the communication aspect. This, they claim, gave rise to a lack of full-picture understanding of challenges and constraints, resulting in suboptimal solutions.

The existing industrial communication standards, such as WirelessHART [4] use conventional routing protocols, which rely on routing tables and graphs and some kind of routing infrastructure, i.e. control message exchange. IWSAN communication is multihop, and distributed routing algorithms are highly preferable. However, data dissemination techniques used in today's industrial communication are inadequate in several aspects:

- *Path recalculation:* In a rapidly changing radio propagation environment, the link failures are frequent, so routing paths have time-limited validity. A broken link can trigger a tedious system recovery process, which leads to routing path recalculation and, consequently, long intervals of IWSAN's unavailability.
- *Control message overhead:* The exchange of routing tables and messages used for network self-recovery or node-discovery poses a significant overhead.
- *Energy consumption:* The existing routing protocols often aim at optimizing the performance with respect to the energy consumption, while sacrificing latency. However, in an industrial environment, sufficient power supply is often readily available [5], and IWSAN nodes are usually not battery-powered.
- *Packet retransmissions:* Transport layer protocols running on top of ACK-based routing protocols initiate retransmissions in case of unsuccessful packet delivery. Having in mind the high dynamics of the observed processes, the data acquired by retransmissions is most probably outdated. Common sense suggests that, instead of re-sending an old piece of data, transmission of a newer measurement should take place.

Thus, it is reasonable to assume that a lightweight, no-frills routing protocol could eliminate some or all of these inadequacies. Flooding is the most rudimentary routing technique, where every node in the network broadcasts all the packets that it receives or generates. Vanilla flooding can cause numerous problems in a wireless sensor network, but, as it will be shown later, its good inherent properties can be exploited after certain modifications.

A. Related Work

Flooding and its variations are used in conventional Wireless Sensor Networks (WSN), which have less strict timing requirements and a number of essential differences, compared to IWSANs. WSN topology in some applications is random, while in IWSANs it is strictly deterministic. Furthermore, the number of nodes in a WSN can range up to several hundreds and even thousands, while IWSANs sensor/actuator populations comprise several dozens of nodes. These differences disqualify the most of conventional WSN routing protocols when it comes to IWSAN applications.

Gossiping and *Flossiping* [6] (and references therein) are flooding-based routing approaches that attempt to avoid the drawbacks of flooding by randomizing the selection of re-transmitters, which is unacceptable in an IWSAN setting. *Graded Back-off Flooding* [7] favors the biggest contributors in terms of one-hop transmission range by allowing them to have smaller back-off times, while *Directed Flooding with Self-Pruning* [8] also takes the remaining energy into consideration. Farivar *et al.* propose *Directed Flooding* [9], allowing the nodes to rebroadcast only if they are located inside the directional virtual aperture of the sender, situated around the straight line that connects source and the sink. Whitehouse *et al.* [10] propose a flooding-based approach that does not fit into the framework of existing industrial communication solutions, because it aims at coverage and proposes medium access techniques that do not adhere to Data Link layer specifications of the existing standards.

Although the listed approaches exploit the paradigm of flooding, they do not correspond to the expectations of data delivery in IWSANs for several reasons. Probabilistic versions of flooding introduce the stochasticity in data delivery, which is inadequate for real-time applications. Furthermore, while flooding in conventional WSNs is usually used for broadcast and aims at coverage, IWSAN uplink delivery paradigm is convergecast. Finally, some of these flooding-based protocols suggest sophisticated and very complex forwarding criteria, whose benefits can only come to the fore in a densely populated WSN, where packets make long journeys. On the other hand, IWSANs are usually 2- or 3-hop mesh networks.

B. Main Contributions

The main contributions of this Paper are:

- We explain how flooding can overcome the aforementioned problems and propose a number of modifications to flooding in order to make it utilizable for uplink in IWSAN applications.
- We evaluate the performance of the proposed solution in a WirelessHART-like network using a discrete-event simulator and show that, if appropriately modified, flooding can be used as a data distribution technique in IWSANs.
- Based on the simulation results, we set boundaries on feasible network size with respect to constraints in terms of latency and reliability.

The remainder of the Paper is structured as follows. In Section II we introduce basic information regarding generic flooding. Section III presents our flooding-based solution. Sections IV and V provide details of the simulated scenarios and discuss the results obtained, followed by Section VI, where we summarize our conclusions.

II. Exploiting flooding in IWSANs

A. The drawbacks of generic flooding

Flooding is a data dissemination technique, where a node transmits or forwards a packet to all of its neighbors. It is the simplest data forwarding technique, and its generic form exhibits a number of drawbacks ([11], [12]):

- *Implosion*: Duplicated packets are delivered to the sink, because multiple copies of a packet travel over different paths.
- *Broadcast storm*: Flooding can produce extreme amounts of redundant traffic, since the number of packets in the network grows exponentially after every hop.
- *Endless packet wandering*: Due to lack of propagation directivity, a packet may circulate around the network for a long time, thus occupying precious network resources.

B. Potentials of flooding in IWSANs

The main benefit of flooding is its utter simplicity. There is no need for exchanging control messages between the nodes and in case of link failures the routing paths do not have to be recalculated. Node failures require no reaction from the network layer, so there exists a smooth transition to the new constellation. Another significant advantage of flooding over conventional routing protocols is that the data is delivered via multiple paths, enhancing redundancy and reliability. The routing information exchange in flooding is virtually non-existent, which leaves more traffic capacity for the actual data traffic. However, the number of multiple paths should be controlled, in order to avoid the network congestion - one of the major causes of latency. The key is to limit the physical scope of forwarding and find the delicate balance between the traffic load, speed and reliability of delivery.

III. The Proposed Flooding Algorithm

A. Flooding design principles for IWSANs

Starting from the generic form of flooding, a number of modifications is introduced, in order to reduce the amount of traffic, while preserving its good properties. This section defines and explains main properties of the proposed approach.

A distributed routing algorithm: Each intermediate node independently decides whether to retransmit or discard the received packet. All the information necessary for making the forwarding decision is extracted or derived from the content of data packets, so there are no control messages.

Handling of duplicates: Every packet contains a unique (i, s) pair, where i stands for the source node address and s signifies the unique application payload identifier. The i parameter unambiguously identifies the originating node, while s is unique for every piece of data sent by that node. Every node should manage a container to store (i, s) pairs of seen packets. Upon reception of a packet, its (i, s) pair is extracted and examined. Duplicates are discarded.

Handling of outdated packets: Packet age is checked at every hop, with respect to the evaluation criteria that will be introduced in one of the following sections. Outdated packets are discarded. The outliers in IWSANs are usually not more than 3 hops away from the sink and the Time-To-Live (TTL) field of data packets should be set with respect to the network topology.

Location-based protocol: A packet must progress towards the sink at every hop. In Stateless Weight Routing [13], the authors introduce the concept of *node weight*. Every intermediate node inserts its weight into the packet and broadcasts it further. The receiving node compares this value with its own weight and decides whether to rebroadcast or drop the packet. The goal is to forward the packet towards the node with a smaller weight than sender's, whereas the sink is assigned the weight equal to zero. Weight w_k of node k should be a superposition of factors such as node positions relative to the sink, current traffic load in the network, or channel state information:

$$w_k = f_{location}(k) + f_{traffic}(k) + f_{link}(k) \quad (1)$$

In this Paper the weights are calculated exclusively from the node's coordinates, i.e. it equals the first term in the above equation. If we define x_k, y_k and z_k as the Cartesian coordinates of the node k, the total weight of node k is:

$$w_k = (x_k - x_{sink})^2 + (y_k - y_{sink})^2 + (z_k - z_{sink})^2 \quad (2)$$

The inserted coordinates represent the only overhead of the proposed solution, which totals several bytes, depending on the desired precision.

Cross-layer support: The considerations in this Paper are not entirely confined to the Network layer and the routing protocols. In order to further enhance the performance of our approach, a simple TDMA scheduling principle is utilized: the nodes which serve as both sources and forwarders of network traffic are assigned more timeslots for transmission than other nodes.

B. Evaluation criteria

IWSAN should deliver sensor readings within the predefined time-frames and with a high level of reliability. The performance of our approach is evaluated through two distinct observables: **1. End-to-end delay**, defined as the time a packet spends traveling between the Application layers of its originator and the sink. It mainly consists of queuing time in the buffers of intermediate nodes, and, to a lesser extent, of in-node processing time along the route to sink; **2. Packet delivery ratio**,i.e. the quotient of the cumulate number of packets sent by Application layers of all the nodes in the network, and the number of packets received in the sink during the simulation. Flooding provides delivery of multiple instances of the same packet to the sink, but each packet will be counted exactly once i.e. the time of arrival of the first copy shall be considered in calculation of average end-to-end delay. We employ these observables to define two evaluation criteria of interest.

Latency requirement: In our model, the sensing devices transmit measurements to the sink at regular intervals. Sensor measurements in process automation have very limited time-validity. Therefore, it is essential that the sink is aware of a particular measurement before a new one is made. The evaluation criterion in this case translates to $T_{e2e} \leq T_{cbr}$, where the variables compared stand for end-to-end delay T_{e2e} and sensor refresh rate T_{cbr}, respectively. Non-compliance with this rule leads to deadline misses and unnecessary occupation of network resources, which can eventually lead to congestion.

Delay-limited capacity: This evaluation criterion combines capacity and outage probability and is expressed in the form of (m, k)-firm deadlines [14] (and references therein), where the loss of at most m out of k consecutive packets is deemed acceptable. We have adopted the values of $m = 2$ and $k = 3$.

C. Forwarding criteria

The five forwarding criteria are the heart of our flooding-based approach, and all must hold in order for a packet to be forwarded.

Condition C_1 states that packet will be considered for forwarding if its age T_{age} is not more than the refresh rate of its originating sensor, T_{cbr}:

$$T_{age} \leq T_{cbr} \quad (3)$$

Condition C_2 holds true for an (i, s) pair if the output of the function $unseen(i, s)$ is logical TRUE, i.e. if a pair (i, s) does not already exist in the container of seen (i, s) pairs:

$$C_1 = unseen(i, s) \quad (4)$$

Every entry (i, s) should be flushed from the container after T_{cbr}, in order to economize memory resources of the node. After this time, the arrival of a packet whose entry has been already flushed will be handled by condition C_1, i.e. it will be discarded, because it will be older than T_{cbr}.

Condition C_3 allows a packet to be considered for forwarding only if its previous hop is a node that lays farther from the sink than the current node, that is if:

$$w_{previous} > w_{current} \quad (5)$$

Condition C_4 holds true if the previous hop of the packet was a node located more than one hop away from the sink, i.e. nodes that have the sink within their range do not need forwarding support.

Condition C_5 implies that if $d(previous, current)$ is the mutual distance between the previous and current hop, the packet can be forwarded only if this distance is smaller than the adopted value of $threshold$:

$$d(previous, current) < threshold \quad (6)$$

The value of $threshold$ is a parameter proprietary to each forwarding node, which will consider a packet for forwarding only if it comes from a node that is less than $threshold$ meters away. By varying this value, a node can reduce or increase the number of neighbors whose packets it considers for forwarding (all five conditions must hold for the forwarding to occur). Every node k has a number of neighbors. If we label as *friends* all the neighbors which, from the perspective of node k, fulfill conditions C_3, C_4 and C_5, then the number of TDMA timeslots that will be assigned to node k must be equal to the number of its *friends*, incremented by one. The explanation is that node k must transmit its own data and forward the data from all of its *friends*, which should be supported by an appropriate number of dedicated timeslots.

This, somewhat contradictory condition, can be motivated as follows. Our approach, albeit being lightweight, is built upon a location-based hierarchy, in conjunction with scheduling. The existence of five forwarding conditions makes it possible to limit the number of forwarders, and, for a given value of $threshold$, the number of forwarders is deterministic. In other words, the number of *friends* of a given nodes is fixed and it can be changed only by modifying the forwarding criteria. In order for the deadlines to be met and to avoid network congestion, the output buffers in the forwarding nodes must perform as sustainably leaky buckets, meaning that their output buffer queues must not grow over time. This is possible only if a forwarder has been assigned enough slots in order to serve all nodes that, from its own perspective, fulfill all five forwarding conditions. Rayleigh fading can cause both extension and contraction of the transmission range. If we consider a network without condition C_5, then, due to Rayleigh fading, a packet can reach too far in one hop and end up at a node which does not have enough slots to serve all nodes that, from its own perspective, fulfill the four conditions. This will trigger a domino effect i.e piling up of packets in queues, network congestion and deadline misses. Therefore, condition C_5 will prevent this by maintaining the balance between the number of packets that should be forwarded within one cycle and the number of available timeslots. This is the rationale behind the decision to discard the packets that come from too far away. The IWSAN topology is deterministic and fixed, and the value of $threshold$ should be downloaded to all the nodes in the initialization phase and adjusted in accordance with network conditions.

Algorithm 1 Proposed solution

Receive a packet (i, s)
if $(C_1 \wedge C_2 \wedge C_3 \wedge C_4 \wedge C_5 = TRUE)$ **then**
  insert (i, s) in table
  $forward(i, s)$
else
  $discard(i, s)$
end if
Go to waiting mode

IV. Simulations

The proposed solution is analyzed in QualNet discrete event simulator on networks placed within a 100 x 100 m area, with a centrally located sink node. This is feasible in practice, because, although there exists zero degrees of freedom in node placement, sinks can be freely positioned in any number. The simulations are time-constrained to 10 minutes, meaning that the nodes are instructed to periodically send measurements throughout the duration of the experiment. The protocol stack is is shown in Table I, composed with the intention to converge to the actual protocol stack of WirelessHART, subject to availability of models in QualNet protocol library.

TABLE I
The simulation parameters

Parameter	Description
Application Layer	CBR application
Transport Layer	UDP
Network Layer	Proposed approach
MAC Layer	TDMA with 10 ms timeslots
Physical Layer	Abstract PHY, SNR-based reception model
Channel Model	Street Microcell [15] with Rayleigh fading
Payload size	32/76 bytes@APPL/PHY layer
Transmit power	10 dBm

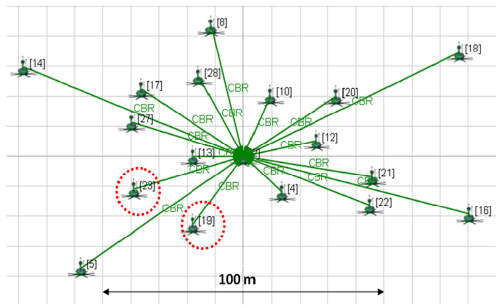

Fig. 1. Network model 1

A. Simulation Scenarios

Our proposed algorithm and several routing protocols are tested against four different scenarios.

Scenario A: End-to-end delay evaluation. The setup from Fig. 1 is simulated under fading-free propagation conditions, in order to isolate the latency issue and focus on generic speed comparison of protocols. The nodes have a refresh rate of $T_{cbr} = 250$ ms and the measurable of interest in this scenario is the average end-to-end delay T_{e2e}.

Scenario B: Robustness to node failure. Conventional routing protocols react to node failures via recovery mechanisms that include route recalculation, which can be a time-consuming process. In this scenario, the node 23 in Fig. 1 is shut down at a certain time-point in the simulation, in order to assess the robustness of the routing protocol in question. The speed of recovery is evaluated by observing the packet delivery ratio (PDR) and the time necessary to establish a new route.

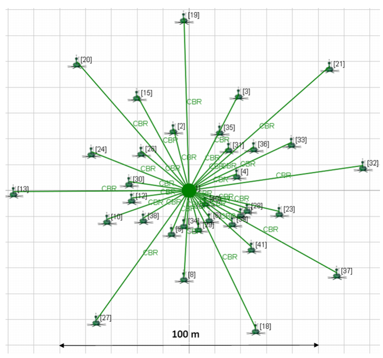

Fig. 2. Network model 2

Scenario C: Robustness to severe channel conditions. The network from Fig. 2 with the refresh rate and deadline of $T_{cbr} = 500$ ms is exposed to Rayleigh fading. Average end-to-end delay and corresponding PDRs are observed.

Scenario D: Constraints in terms of node population size. This scenario investigates the maximum feasible network sizes the with respect to $T_{e2e} \leq T_{cbr}$ and $(2,3)$-firm deadline criteria. The assumptions are that 75% of the nodes are one hop away from the sink and that remaining 25% are two hops away and have at least two neighbors within range. This was achieved by adjusting the value of *threshold*.

B. Assumptions and Delimitations

Assessment of the proposed solution against the two evaluation criteria is of the uttermost importance in this Paper, whereas the comparison with the selected benchmark ad-hoc WSN protocols has an illustrative purpose.

TDMA is chosen as the medium access technique, in accordance to the Data Link layer specification of WirelessHART. Although this technique is usually avoided by authors, it provides deterministic performance in terms of average end-to-end delay and removes the possibility of packet collisions, which makes it suitable for IWSAN applications.

The SNR-based reception model at the Physical layer implies that a whole packet is lost if its RSS does not exceed the reception threshold. This mechanism emulates slow Rayleigh fading, where entire packets are lost. In the simulations, the RSS fluctuates in the range between -57 ÷ - 84 dBm, which is similar to the values from a real-life case study presented in [16].

V. Simulation Results

Our solution outperforms the other routing protocols in all scenarios of interest and meets both $T_{e2e} \leq T_{cbr}$ and $(2,3)$-firm deadline requirements for all results presented in this section. This is the reason why end-to-end delay is quantified through its average value, and not through its distribution or confidence intervals - outdated packets are discarded on-the-fly in the intermediate nodes and do not participate in collection of final statistics.

A. Scenario A

Table II shows average end-to-end delays observed in Network model 1 for sensor refresh rate of $T_{cbr} = 250$ ms. Our utterly lightweight routing protocol meets both evaluation criteria, with latency which is 74% below the deadline, while the conventional routing protocols cannot cope with the given traffic load, resulting in much higher latencies.

TABLE II
Average end-to-end delays for the network from Fig. 1 and $T_{cbr} = 250$ ms (i.e. 1024 bits/s/node)

Routing protocol	**Average end-to-end delay**
Proposed solution	91 ms
AODV	7178 ms
DYMO	6623 ms
DSR	9402 ms
LAR1	4352 ms
OLSRv2 Niigata	17458 ms
STAR	11412 ms

B. Scenario B

In Scenario B, node 5 from Fig. 1 loses one of its neighbors, namely node 23. Our approach exploits two paths in parallel to deliver data from node 5 to the sink (via nodes 23 and 19), and the failure of one path will not cause interruptions in data delivery. Conventional routing protocols using node 23 to deliver data from node 5 will take certain time to recalculate the routing path and shift it to node 19, which will affect the latency. From the perspective of a unicast routing protocol, this is a trivial scenario, because the failing node 23 has only two neighbors, and the procedure of establishing a new path should be quite straightforward. The *recovery times*, defined as the time between a node failure and reestablishment of the route via an alternative path, are shown in Table III. The corresponding PDRs are presented in Fig. 3. Our approach achieves 100% PDR, whereas its closest follower, DSR, delivers around 91%. The results suggest that our solution has a seamless transition in the event of topology change, which does not hold for other protocols examined.

TABLE III
Recovery times for various routing protocols

Routing protocol	**Recovery time**
Proposed solution	0 sec
AODV	$\geq$ simulation time
DSR	297 sec
DYMO	305 sec

C. Scenario C

Fig. 3 presents PDRs of routing protocols in Network model 2 under Street Microcell propagation model [15] combined with Rayleigh fading. For $T_{cbr} = 500$ ms our approach exhibits PDR of 84.28%, the highest of all protocols observed. Average end-to-end delay of the proposed solution is well below the 500 ms deadline, as shown in Table IV. Similarly to Scenario B, the good performance stems from the redundancy of multipath.

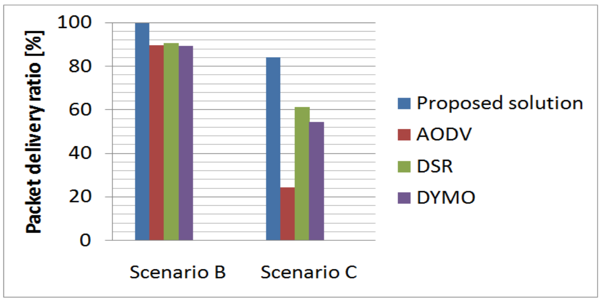

Fig. 3. Packet delivery ratios of Scenarios B and C

TABLE IV
AVERAGE END-TO-END DELAYS FOR SCENARIO C (RAYLEIGH FADING)

Routing protocol	Average end-to-end delay
Proposed solution	183 ms
AODV	183030 ms
DSR	48173 ms
DYMO	68025 ms

TABLE V
FEASIBLE NETWORK SIZES AND CORRESPONDING AVERAGE END-TO-END DELAYS FOR THE PROPOSED SOLUTION

Refresh rate	Maximum network size	Average end-to-end delay
250 ms	16 nodes	91 ms
500 ms	33 nodes	183 ms
750 ms	50 nodes	356 ms
1000 ms	65 nodes	457 ms

D. Scenario D

Fig. 4 shows the dependency of latency on network population size. The observed networks have a sensor refresh rate of $T_{cbr} = 1$ sec and 75% nodes located one hop away from the sink. The simulation results indicate that our solution allows the use of larger networks than all other protocols, with respect to the latency constraint. According to the results, AODV, DYMO and DSR can meet the demands of the two evaluation criteria only for networks of up to 20-25 nodes, whereas the average end-to-end delays exhibited by our approach stay well below the deadline throughout the observed range of network sizes. The latency curve of our solution has a constant slope, while the latencies of other routing protocols explode around the 18-node mark.

In order to further assess the performance of our solution, we have determined the maximum network sizes that it can support for sensor refresh rates of 250, 500, 750 and 1000 ms. The networks are built up iteratively, following the previously defined 75%-25% assumption. The results in Table V illustrate the maximum node populations that can satisfy the $T_{e2e} \leq T_{cbr}$ and $(2, 3)$-firm deadline criteria. The feasible network sizes are sufficient for the majority of IWSAN applications. The need for a larger network can be satisfied by deploying additional sinks, thus partitioning the overall node population into smaller entities.

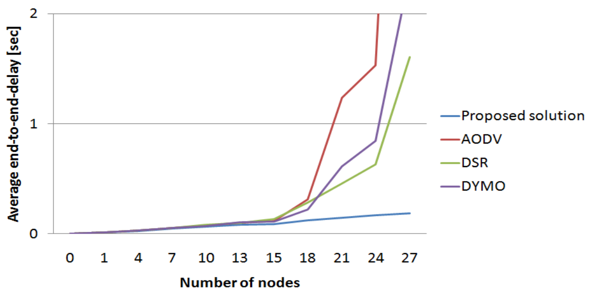

Fig. 4. Average end-to-end delay as a function of network size

VI. CONCLUSIONS AND FUTURE WORK

In this Paper we show that flooding can be efficiently used for data dissemination in IWSANs, under certain conditions and minimal modifications. The simulation results suggest that our approach is capable of delivering data faster and more efficiently than the other routing protocols examined, with significantly less complexity. The latency is highly correlated with topology size and sensor refresh rate, and networks comprising up to several dozens of nodes can meet the timing and reliability requirements, which is sufficient and relevant for real-world IWSAN deployments.

The future work in this area should consider further enhancements of the proposed solution, such as optimization of scheduling, data aggregation and further development of the weight concept, to name a few.

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APPENDIX A: Some experiences from using QualNet 5.0

Physical-MAC layer compatibility issues in QualNet

QualNet 5.0 does not support interoperability of 802.15.4 Physical and TDMA MAC layer. The solution is to use the *Abstract* Physical layer model, which is compatible with TDMA. Abstract PHY comes in two reception modes: SNR-based and BER-based. Both models require the user to define the *reception sensitivity* and *reception threshold*. In the case of SNR-based model, the received signal with RSS below reception sensitivity will not be detected. Additionally, for a packet to be correctly received, its RSS must be above the reception threshold as well. BER-based model enables the user to provide BER tables that will define BER for a given SNR. In this work, SNR-based model is used, with the values of reception sensitivity and reception threshold corresponding to the ones that WirelessHART prescribes.

Average end-to-end delay calculation in QualNet

QualNet calculates the average end-to-end delay in a rather unusual way, by summing up average delays for all the nodes in the network. In order to obtain the average end-to-end delay in the network as defined previously in this Thesis, one must divide the end-to-end delay provided by QualNet with the number of nodes in the network, excluding the sink.

APPENDIX B: IWSN topologies used in scenarios

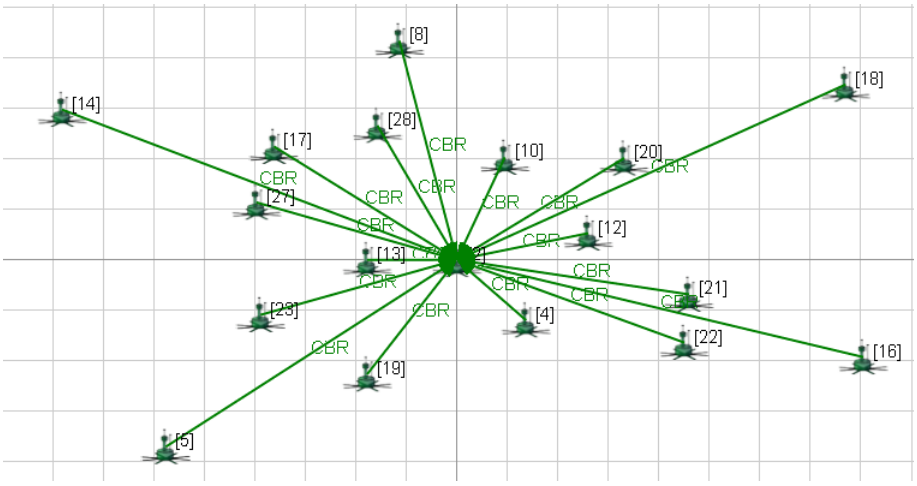

Figure 11: IWSN model for Scenario A1

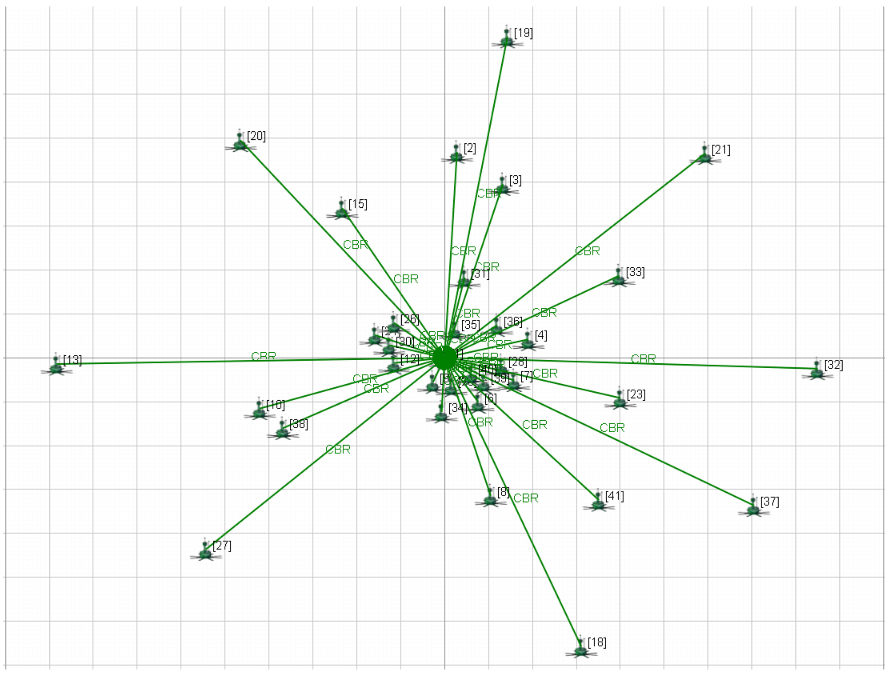

Figure 12: IWSN model for Scenario A2

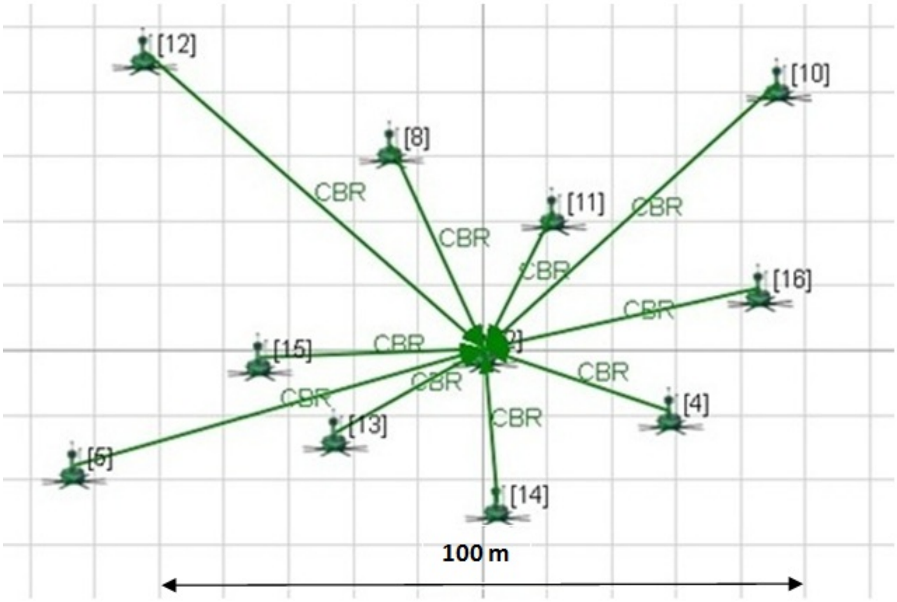

Figure 13: IWSN model for Scenario B

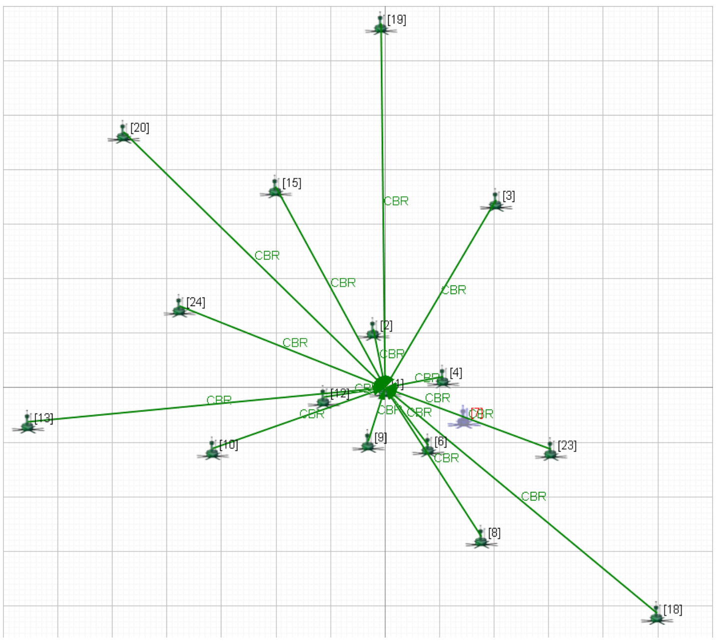

Figure 14: IWSN model for Scenario C1

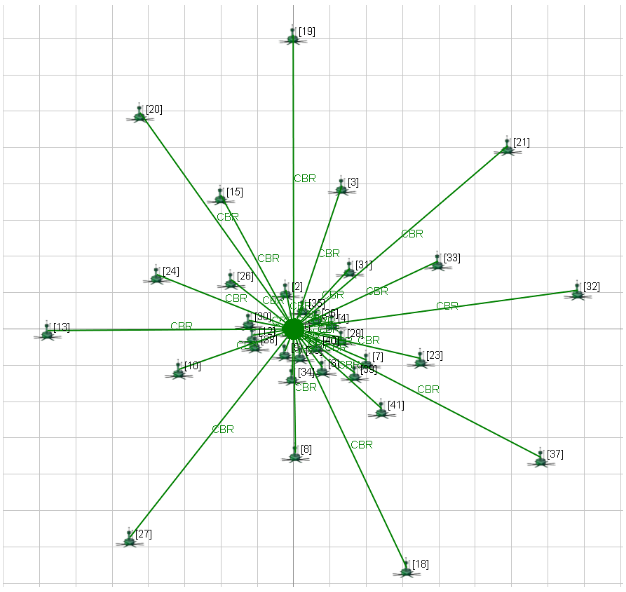

Figure 15: IWSN model for Scenario C2

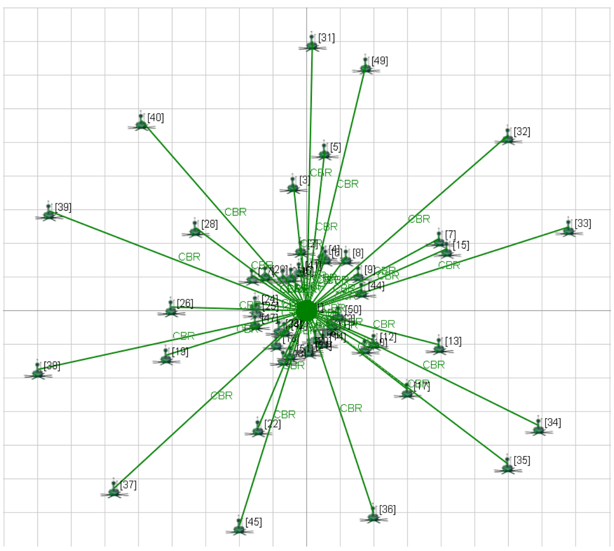

Figure 16: IWSN model for Scenario C3

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