Opportunistic Routing in LoRa-based Wireless Mesh Networks

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***Abstract*—The recent move of the LoRa wireless technology towards the wider 2.4 GHz ISM spectrum band creates multiple opportunities for its broader usage in new IoT applications requiring larger data rates. However, this ISM band is already crowded with other wireless technologies like WiFi or Bluetooth, and cross-technology interference issues need to be considered. Moreover, the less favorable radio propagation properties in the 2.4 GHz band shorten the communication distance of LoRa transmissions and therefore make relaying necessary. Unfortunately, the direct usage of LoRa technology in a wireless mesh network is challenging due to the non-existent generic frame preamble and header, i.e. LoRa frames are not self-contained. This makes the dynamic adaptation of the modulation used by LoRa per link or even packet transmission challenging. We show in this paper that such limitation can be partially overcome by utilizing the macro spacial diversity provided by opportunistic routing (OR) protocols. In contrast to traditional routing OR selects a candidate set of nodes per hop along the path in the mesh network. Thus any temporal channel fading and local interference conditions will not result in a failed transmissions due to utilization of the spatial diversity provided by OR. The usage of OR achieves a much higher E2E packet delivery rate as well as lower E2E delay as compared to traditional routing while the overhead is reasonable. Moreover, with OR the same signal modulation can be used network-wide and its adjustment can be made on a long-term basis.**

***Index terms*—** IoT, LoRa, wireless mesh networks, opportunistic routing

I. Introduction

Today, we see an increase in the number of IoT devices and its applications [1]. Due to its long communication range [2], [3] and usage of unlicensed spectrum Lora is a promising technology for the IoT. The technology was introduced by Semtech in 2012 [4], [5] with a promise of communication ranges of up to 15 km and low energy consumption [3]. First LoRa was introduced in the 433/868 MHz ISM spectrum bands [6]. Since 2017, LoRa can also be used in the 2.4 GHz ISM band [2], [4], [6]. This creates opportunities for new IoT applications as restrictions like a maximum duty cycle of 1% are not necessary [2], [7]. Moreover, improvements in the physical layer like the possibility of wider channels further increase the data rate of LoRa in the 2.4 GHz band [2], [6].

However, moving from sub-GHz to 2.4 GHz ISM band comes with a caveat. The communication range shrinks dramatically. Furthermore, the influence of Shadowing by obstacles is significantly higher, i.e. a single large building blocking the line-of-sight (LoS) path can interrupt the communication [8]. LoRa can tackle this problem by adjusting the

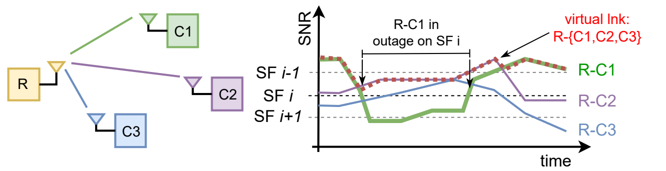


Fig. 1: Key idea: As the LoRa SF is fixed `OppLoRa` utilizes anycast transmissions to handle temporal drops in link SNR.

so-called spreading factor (SF) which changes its signal modulation and hence influences the data rate and the robustness of the LoRa signal.

A LoRa wireless mesh network (WMN) can overcome the range limitations in the 2.4 GHz band by enabling multi-hop relaying. With a sufficient node density a signal blockage by an obstacle do not pose serious problems as the traffic can be routed over a different path. WMNs are already well studied, however, LoRa has peculiarities. Unlike technologies like IEEE 802.11 it lacks a generic frame preamble and header, i.e. frames are not self-contained. Hence, any change in the LoRa SF must be communicated by the transmitter to the receiver beforehand or some signaling over some out-of-band control channel is needed. From the practical point of view both approaches are unsuitable. Another, but expensive approach, is to use LoRa receivers which are able to decode multiple SFs in parallel. Finally, there is the option to use just a single network-wide SF.

However, the usage of expensive hardware components which can decode multiple SFs in parallel opposes the idea of a low-cost LoRa-based WMN, as a large amount of devices will be needed. The same applies when using additional hardware for out-of-band signaling. Thus, we require the LoRa WMN to operate on the same SF, which can, however, be adjusted medium to long-term if necessary. This raises the issue of temporally broken links due to shadowing from obstacles or temporal cross-technology interference (CTI). Classical link error-control mechanisms make use of automatic repeat request (ARQ) to retransmit frames if transmission failed. Often those are used in combination with Adaptive Coding and Modulation (ACM) where the modulation is adapted to use more robust modulations, i.e. higher SF in case of LoRa, for retransmissions. As such an approach is not applicable in LoRa we target this problem with a cross-layer approach by exploiting the advantages provided by opportunistic routing

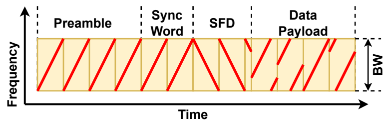


Fig. 2: Frame structure of LoRa [14]

(OR). OR belongs to the class of any-cast routing schemes which exploit the broadcast nature of the wireless medium to increase efficiency [9]. Our key idea of utilizing OR in LoRa-based WMNs is as follows (Fig. 1). Instead of repeating the transmission of a frame on a temporally broken link again and again, OR uses multiple nodes as potential next hop forwarders for the same transmission. Here the transmission is successful if at least one of the candidates receives the frame for later forwarding. The macro spatial diversity provided by OR allows us to overcome the issue of temporally broken links in a LoRa WMN.

Contributions: In this paper, we introduce `OppLoRa` a LoRa-based WMN based on OR. Results from simulations reveal that `OppLoRa` is able to dramatically improve the end-to-end (E2E) reliability as compared to traditional approaches. Moreover, the E2E delay is lower and the overhead in terms of channel utilization is comparable to traditional routing as well as cross-layer approaches.

II. LoRa Primer

LoRa is a narrow-band long-range wireless technology providing reasonably low data rate sufficient for a variety of IoT applications. A LoRa sender emits discrete frequency ramps, the so-called chirps [5]. A chirp uses the available bandwidth (BW) which is a configurable parameter [10]. When using the 2.4 GHz ISM band the bandwidth ranges from 203 kHz up to 1625 kHz [11]. Moreover, a chirp is divided into 2^{SF} chips [5], [12] while the duration of each chip is $\frac{1}{BW}$ for which the frequency of the LoRa signal is constant [5]. The parameter SF describes the length of a chirp and thereby its angle [5]. Both the SF and BW control the robustness of a LoRa transmission. A small BW with a high SF creates a slowly changing LoRa signal and gives LoRa the opportunity of a long distance communication as the receiver sensitivity goes down to -132 dBm [13]. However, the raw data rate decreases down to 595 bps when using SF12 with BW=203 kHz (compared to 253 kbps when using SF5 with BW=1625 kHz) [13]. LoRa uses up-chirps for the preamble and the data symbols. Only the start frame delimiter consists of 2.25 down-chrips as Figure 2 shows. The symbol value is coded into the shift of the start frequency of the chirp [14]. Unlike technologies like 802.11 or 802.15.4 LoRa lacks a generic frame preamble and header, i.e. LoRa frames are not self-contained. Hence any change in the used BW and SF needs to be communicated to the intended receiver before the actual transmission. The only exception are high-cost LoRa gateways which are able to decode multiple SF and BW configurations in parallel. On the medium access control (MAC) layer LoRa uses basic ALOHA protocol for the channel access. However, LoRa makes heavy use of the so-called capture effect to improve the channel capacity. Hence, a receiver can decode a frame with signal to interference ratio (SIR) of 0 dB once its phase-locked loop (PLL) is locked to the transmission [15]. Experimental results reveal an increase by a factor of two [16], [17] or even six [18] compared to classical ALOHA.

III. The OppLoRa Approach

In the following, we give a detailed description of the proposed `OppLoRa` approach which is a WMN based on OR. It uses a reliable anycast data link layer (MAC) and standard LoRa on the physical layer.

A. Routing Decisions and Forwarding

`OppLoRa` uses OR as routing protocol. OR belongs to the class of cross-layer and anycast routing protocols. Instead of sending a packet to one next hop along the route, OR sends the packet to multiple neighboring nodes termed as candidate set (e.g., $\{C1, C2, C3\}$ in Fig. 1) [9]. Therefore, it exploits the broadcast nature of the wireless medium [9], [19]. This comes with the advantage that a transmission is successful if at least one of the next-hop candidates receives the packet (anycast). An OR protocol has to face several tasks, like the calculation of the candidate set and the coordination among the candidates to decide on the next forwarder. `OppLoRa` uses a modified version of the ExOR [9] protocol combined with a DSDV route discovery. The candidate set (CS) is computed on each hop by the respective forwarding node F. Therefore, F takes all neighboring nodes N_i having a smaller number of hops towards the final destination. In addition we demand that the nodes inside the CS form a clique, i.e. there is a link between any pair of nodes from the CS. This restriction makes sure that the candidates hear other's transmissions and therefore are able to decide whether they need to drop or forward the packet. Hence, nodes which are not in the clique are removed from the CS. Finally, we rank the candidates inside the CS according to their hop distance to the destination node in ascending order, i.e. the candidate which is closest to the destination has the highest rank. Note, that the size of the CS can be limited. In such a case we select from all possible cliques the clique with the highest sum of signal strength of the links within the clique as well, as of the links between each member in the clique with F.

OR like other anycast routing protocols is vulnerable to packet duplication. In case the mutual voting among the nodes in the CS on the next forwarder fails, a duplicate packet is created as the same packet is forwarded by multiple nodes [9], [20]. To avoid this waste of radio resources `OppLoRa` uses an aggressive duplicate detection and elimination scheme. It is based on overhearing others nodes packets. E.g., in case a node overhears an ongoing transmission of a packet which is waiting in its own transmission queue, it can drop that packet from its queue.

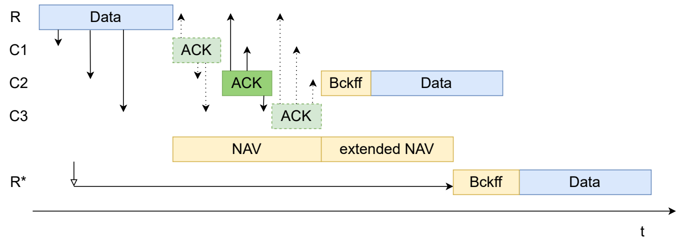


Fig. 3: Anycast-MAC in OppLoRa: slotted acknowledgments (ACKs) and virtual channel reservation using network allocation vector (NAV).

B. Medium Access

OppLoRa extends the standard ALOHA MAC protocol to coordinate distributed channel access. It supports the OR by providing on the data link layer a reliable anycast transmission to the selected next hop CS. This is achieved by having a slotted ACKs protocol (Fig. 3) as proposed in [21]. It is used to acknowledge the reception of the data frame by the next hop candidates towards the sender and provides coordination among the nodes in the CS to find the best relay to forward the frame. The coordination works as follows: First, the sender broadcasts the packet to all relays in the CS. These candidate nodes are addressed in the header of the LoRa data frame. Within the address field the nodes are ordered by their rank. This assigns a priority to the different candidates which defines the order in which the ACK frames are sent [9]. Therefore, at first, the preferred next hop is allowed to send its ACK. If this node does not receive the packet, the node of second rank ($C2$) notice that by not receiving the ACK. Thereby, $C2$ will send its ACK. If $C2$ do not get the frame, the node of rank three will acknowledge the transmission and so on. By receiving an ACK frame, the sender marks the transmission as successful. The relay node which sends the ACK becomes the new sender and is responsible for forwarding the packet towards the destination [9]. Whenever a node is responsible to forward a packet it will do it immediately. However, there is an exception to this rule. If a node should forward a packet for the second or more time, i.e. routing loop, we have the situation that the link towards some important hop or the final destination is temporarily not available. In such a case, the node delays the packet transmission to give time for the link to recover.

Additionally, we use virtual channel reservation using network allocation vectors (NAVs) to avoid collisions between ACK control packets and the forwarded data packets as well, as other nodes competing for the channel (Fig. 3). Therefore, all nodes have to decode the NAV value from all overheard packets and stay silent for the given duration. Nodes not being in the candidate set have to follow the extended NAV to avoid collision with the relayed packets. This extension is needed, due to the missing physical carrier sensing in ALOHA protocol and the particularities of OR. Before a node from the CS is allowed to forward the packet, it must wait for the ACKs of the other candidates. In addition a random backoff is performed. The later is needed to avoid synchronization of multiple transmitters which can cause packet collisions, e.g. if the coordination between the candidates fails and multiple node start forwarding the packet. The backoff is computed as follows:

$$t_{backoff} = t_{frame} \times U(5, \max(5, (16 - 1.2 \times txqlen))) \quad (1)$$

where t_{frame} is the duration of a typical LoRa frame. Note, that the backoff takes into account the number of packets queued for transmission, $txqlen$, which is used to give overloaded nodes a higher chance to access the channel.

Whenever the MAC anycast operation fails, i.e. not a single ACK is received by the sender, the packet is given back to the OppLoRa network layer, which generates a new routing decision with a possible new CS. After an additional random delay, following a Gaussian distribution $N(500 \cdot t_{frame}, 150 \cdot t_{frame})$ the frame is retransmitted. The number of retries is set to three.

C. Physical Layer

OppLoRa uses unmodified LoRa on the physical layer. In the WMN, all nodes are equipped with a single low-cost LoRa radio. The radio is operating on a single channel in a half-duplex mode. Thus, a device can receive only a single LoRa packet at a time. Finally, all nodes in the WMN are configured to operate on the same SF and BW configuration which can be adapted on a long-term scale, i.e. once per day or on joining/leaving of new nodes.

IV. Evaluation

We evaluate OppLoRa by means of simulations. Specifically, the following approaches are compared:

- OppLoRa - proposed approach with different CS sizes,
- TR - traditional routing,
- CL - cross-layer approach

The traditional routing (TR) approach uses DSDV [22] which is a proactive unicast distance vector routing protocol. In case of a failed transmission on the data link layer the packet is retransmitted over the same link until it is either successful or reaches the maximum number of retries. Hence, the routing decision is not changed between retransmissions. In the cross-layer (CL) approach the data link layer returns the packet back to the network layer in case the transmission failed. This gives the network layer the possibility to select another next hop forwarder to be used for the retransmission. Hence the CL routing is a special case of OR routing with a clique size of one. All three approaches are parameterized with a link margin γ. Only links with a link budget of more than γ are considered and therefore used for the routing. A large γ keeps only high SNR links but reduces the number of potential neighbors and hence the meshing.

A. Experimental Methodology

The aforementioned approaches are evaluated in a custom system-level packet simulator. In order to realize realistic LoRa network scenarios, for the placement of the LoRa nodes, we used the data provided by OpenStreetMap. Specifically, three environments were selected. The first environment is around the university campus of Technische Universitaet Berlin, a second environment is an urban scenario in the center of Berlin and a third environment is a village with smaller buildings in the west of Berlin. For the simulation, the LoRa mesh nodes were randomly placed within buildings only. Two different node densities of 30 nodes/km^2 and 100 nodes/km^2 were used. The nodes were placed in such a way that the network graph was connected when using SF 7 and no Shadowing. All in all, 23 different networks are calculated. During each simulation run a single packet flow between two randomly selected nodes were created and simulated for the duration of 1000 s. The packets arrival time at the source was generated according to a Gaussian distribution $N(1\,\text{s}, 0.25\,\text{s})$. A proactive route discovery with an update interval of 10 s was simulated out of band. As channel model for LoRa, a LoS path loss model with additional Shadowing is used, as recent literature proposes [23], [24]:

$$\begin{aligned} P_{pl} = {} & 56 + 20\log_{10}(f[\text{MHz}]) + 20\log_{10}(d[\text{km}]) \\ & + P_{shad,TX} + P_{shad,RX} \end{aligned} \quad (2)$$

This channel model takes the Shadowing from both the sender and the receiver into account. In order to model spatial correlation of the Shadowing values a shadow map is calculated and updated at random points in time following a Gaussian distribution $N(25\,\text{s}, 10\,\text{s})$. The shadow map uses a grid of 10 m and the Shadowing follows a log-normal distribution $N(0\,\text{dB}, 3\,\text{dB})$. Based on this map the Shadowing at the position of the receiver is interpolated. All in all, the resulting Shadowing of a link follows a log-normal distribution $N(0\,\text{dB}, 6\,\text{dB})$, which is observed by Rahmadhani et al. [24] for the city of Emmeloord. For a specific point in time the shadow value is linearly interpolated. The remaining simulation parameters are summarized in Table I.

The following metrics were selected for the comparison:

- E2E packet error ratio (PER),
- E2E delay,
- channel usage.

Note, that the channel usage is computed as the accumulated airtime divided by the duration of the simulation.

TABLE I: Simulation parameters

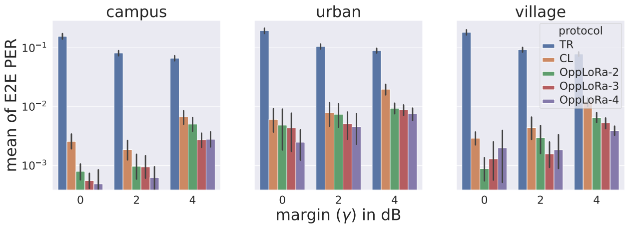
Parameter	**Value**
Spreading factor	fixed SF 7
Bandwidth	1.625 MHz
Spectrum	2.4 GHz (ISM)
Code rate	5/4
Transmission power	12.5 dBm
Environments	campus, urban, village
Margin (γ)	[0 dB, 2 dB, 4 dB]
Density	$[30\frac{\text{nodes}}{\text{km}^2}, 100\frac{\text{nodes}}{\text{km}^2}]$
Packet generation (src)	$N(1\,\text{s}, 0.25\,\text{s})$
Link probing interval	10 s
Backoff before retransmission	$N(500t_{t_{frame}}, 150t_{t_{frame}})$
Backoff after transmission	$4.6\,\text{ms} \cdot U(5, \max(5, (16 - 1.2 \cdot txqlen)))$
Simulation duration	1000 s
Shadowing update interval	$N(25\,\text{s}, 10\,\text{s})$
Shadowing σ (per node / link)	3 dB / 6 dB

B. Results

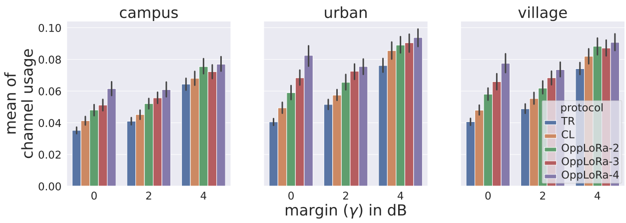
Fig. 4 shows the results for the low density scenario with 30 nodes/km^2. We clearly see the improvements in terms of E2E PER for the proposed `OppLoRa` approach which is mainly due to the utilization of the spatial diversity provided by OR. This is supported by the observation that with increase in the maximum CS size the E2E PER can be further decreased. The CL approach outperforms the traditional approach (TR) by one magnitude because of the possibility to change the next hop for retransmissions. By increasing the margin γ the E2E PER of the TR approach can be decreased caused by only strongly connected next hop forwarders are selected. This technique makes the communication more resilient to channel changes at the cost of more hops. In contrast there is no advantage for `OppLoRa` of having a γ above 0 which can be explained by the unnecessary restriction of the potential next hop forwarders which is limiting the gain from OR. `OppLoRa` outperforms the technique of increasing the margin γ. In terms of overhead, i.e. channel usage, the TR approach performs best. However, this must be seen in relation to the high PER - fewer packets are simply delivered to the destination. `OppLoRa` consumes the most channel resources especially with higher CS size which is mainly due to the overhead of coordination between the nodes in the CS (transmission of ACK packets) as well the possibility of the creation of unwanted duplicate packets which consume valuable radio resources. This is the price which has to be paid to achieve the lowest E2E PER as well as E2E delay in `OppLoRa`. `OppLoRa` achieves the lowest E2E delay when using a large CS whereas the CL approach performs worse. Finally, we see that a larger margin γ increases the E2E delay which is because of the larger number of E2E hops needed to reach the destination.

For comparison, Fig. 5 shows the results for the high density scenario with 3.3× more mesh nodes per km^2. Again, we see that `OppLoRa` outperforms the other two approaches in terms of E2E PER as well as E2E delay. Interestingly, all three approaches have a similar channel usage. Moreover, the high density of nodes in the network allows the usage of larger γ which helps to further bring down the E2E PER for all the three approaches whereas the impact on the E2E delay is not so clear. Finally, Fig. 6 shows the three performance metrics in one spider plot for the urban scenario. We can clearly see that `OppLoRa` outperforms all other approaches.

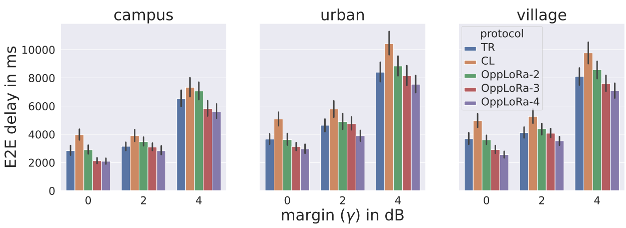
Summary: In a LoRa mesh network with low node density the proposed `OppLoRa` approach is able to outperform both the traditional as well as the cross-layer approach in terms of E2E PER and E2E delay but at a slightly higher channel usage. The advantage of `OppLoRa` increases with node density while



(a) E2E PER

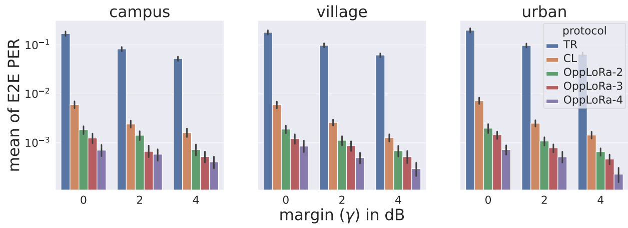


(b) channel usage

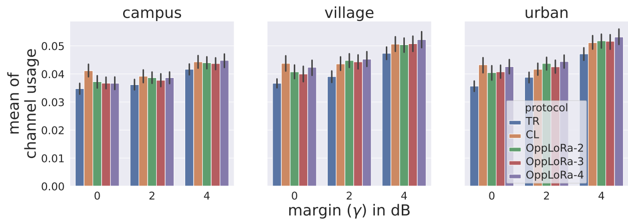


(c) E2E delay

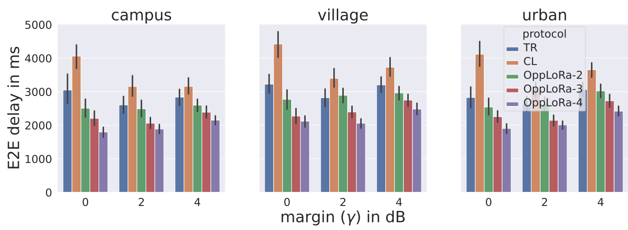
Fig. 4: E2E PER (logarithmic scale), channel usage and E2E delay for the three environments and node density $30\,\text{nodes/km}^2$.



(a) E2E PER



(b) channel usage



(c) E2E delay

Fig. 5: E2E PER (logarithmic scale), channel usage and E2E delay for the three environments and node density $100\,\text{nodes/km}^2$.

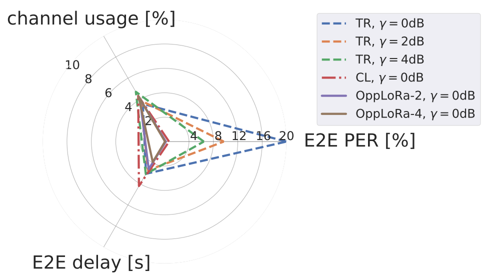


Fig. 6: Spider plot summarizing results for a node density $100\,\text{nodes/km}^2$ in urban scenario.

the channel usage becomes comparable to that of the other approaches.

V. Related Work

`OppLoRa` is related to past work on the usage of LoRa radio technology in wireless mesh networks. A multitude of works focused on adapting the LoRa MAC layer to make it more suitable for WMNs. Instead of using the rather inefficient ALOHA protocol the usage of carrier sense multiple access (CSMA) was proposed in [25], [26] whereas other groups proposed the usage of time devision multiple access (TDMA) [15], [27]. `OppLoRa` still uses the simple ALOHA protocol because packet collisions are less of a problem for anycast transmissions and the capture effect is high in LoRa.

Besides improvements on the MAC layer some researchers focused on the routing inside a LoRa-based WMN. Tree-based routing was proposed by Toldov et al. [26] and Satori et al. [28]. Here the routing protocol creates a tree structure which is used to route traffic from the mesh nodes towards the LoRa gateway. A similar approach was proposed by Lee et al. to use such a tree structure to enable the gateway to poll the stations [29]. Pham et al. [30] analyzed energy consumption and showed, that their reactive routing protocol is able to save energy [30]. Finally, Huh et al. [31] proposed a joint distributed queuing protocol to achieve load balancing inside a LoRa WMN. OR is an efficient routing strategy in WMNs as it utilizes the broadcast nature of the wireless transmission in order to increase the E2E reliability [9], [20], [32]. Moreover, it can adapt faster to link and network changes. Hawbani et al. [33] proposed the usage of OR in energy-constrained low duty-cycled wireless sensor networks which use asynchronous MAC protocols. This allows to reduce the E2E packet delay as with a sufficient large CS size the sender's waiting time could be reduced significantly. However, `OppLoRa` is different as it utilizes the macro spatial diversity provided by OR to overcome the problems of signal fading and CTI.

VI. Conclusion

The direct usage of 2.4 GHz LoRa technology in a low-cost wireless mesh network is challenging due to the not existing generic frame preamble and header which complicates the dynamic adaptation of the LoRa spreading factor (SF). In this paper we presented `OppLoRa` which utilizes the macro spatial diversity provided by opportunistic routing in order to be resilient towards temporal channel fading and local interference. Simulation results reveal a much higher E2E packet delivery rate and lower E2E delay as compared to traditional routing schemes while the the overhead was reasonable.

As future work we plan to prototype `OppLoRa` and evaluate its performance in a real outdoor testbed. This is feasible as the envisioned system can be implemented using COTS LoRa hardware. This would allow us to quantify its performance under real channel and interference (e.g., from WiFi) conditions. Additionally, a co-design of the MAC protocol towards energy efficiency would enable to use `OppLoRa` on battery-powered devices.

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