Implicit Multi-hop Communication Scheme based on Overhearing in IoT LoRa Networks

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***Abstract*—Long Range (LoRa) is a Low-Power Wide-Area technology, because it is eminent for robust long-distance, low-bit rate, and low power communications in the unlicensed sub GHz spectrum used for the Internet of Things (IoT) networks. Recently, several schemes in multi-hop LoRa networks have proposed schemes with explicit relay nodes to partially mitigate the path loss and longer transmission time bottlenecks of the conventional single-hop LoRa by focusing more on coverage expansion. However, they do not consider improving the packet delivery success ratio (PDSR) and the packet reduction ratio (PRR) by using the overhearing technique. Thus, this paper proposes an Implicit Multi-hop Communication scheme based on Overhearing (IMCO) that exploits implicit relay nodes for performing the overhearing to promote relay operation. In IMCO, implicit relay nodes are selected as overhearing nodes (OHs) among end devices which have a Low spreading factor (SF) to improve PDSR and PRR for distant end devices (EDs). A theoretical framework for designing and determining the OH nodes to execute the relay operations was developed with consideration of the LoRaWAN MAC protocol. Simulation results verify that IMCO achieves better performance than the existing schemes.**

***Index Terms*—Long Range, LoRaWAN, Spreading Factor, Bit Error Rate, Received Signal Strength Indicator.**

I. Introduction

The Internet of Things (IoT) services have gained popularity as they continue to impact on society in numerous application domains such as industry IoT (IIoT), smart farming, smart metering, remote health care, etc [1] [2]. IoT is becoming increasingly ubiquitous in smart objects with which has necessitated smart industry to perform various smart error free functions and enriched automation processes [3] [4].

Low Power Wide Area Networks (LPWANs) have emerged as an IoT backbone to enable low-cost network deployment, constrained power consumption and long lifetime. LPWAN solutions constitute robust modulation and low data rates to attain a long coverage communication range that enables IoT applications to obtain the desired level of performance [5]. The study reported in [6] [7] elucidate the reliable, efficient and resilient LPWAN technologies for IoT networks such as; LoRa (Long Range), Sigfox, Narrow band Internet of things (NB-IoT) and Ingenu. LoRa networking is predominantly deployed in LPWAN applications because it's an open-source and unlicensed Industrial, Scientific and Medical (ISM) sub-GHz band that enables autonomous network set up at a low cost, therefore this makes it compatible in IoT applications [8] [9]. LoRaWAN is the standard MAC layer for LoRa which adopts the star of stars topology in which an end device's communication to the server goes through the gateways as shown in Fig. 1.

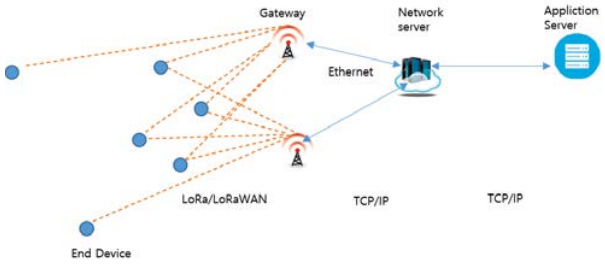


Fig. 1. Simple topology for LoRa Network.

LoRa is a proprietary Chirp spreading spectrum modulation scheme developed and patented by Semtech. This enables long-range, low data rates communication over the license free sub 1 GHz ISM bands. The effectiveness of Long range (LoRa) depends on a link budget which can be modified through changes in code rate (CR), Bandwidth (BW), transmission power (Tx) and spreading factor (SF) [10] [11].

Conventional LoRa networks are single hop, with end devices (EDs) connected to a centralized gateway (GW) through a direct link, which may cause path loss, longer transmission time, and interference to distant EDs with high Spreading SF. Thus, causing an outage of the desired signal in the uplink at the GW. In addition, signal outage at the GW may arise as a result of Received signal to noise ratio (SNR) being below the threshold for each SF required

for error-free decoding, when signal strength falls below the sensitivity of the receiver and collisions as a result of concurrent transmission [12]. Recently, several schemes in multi-hop LoRa networks have proposed schemes with explicit relay nodes to partially mitigate the path loss and longer transmission time bottlenecks of the conventional single-hop LoRa by focusing more on coverage expansion. However, they do not consider improving packet delivery success ratio (PDSR) and the packet reduction ratio (PRR) by using the overhearing technique.

Therefore, this article proposes an Implicit Multihop Communication Scheme based on Overhearing (IMCO). The IMCO scheme exploits implicit relay nodes for performing the overhearing to promote relay operation. This is achieved through overhearing nodes(OHs) with a Low SF to improve the PDSR for distant EDs. Herein, the selected overhearing node(s) closer to the gateway with a low SF and lower Bit Error Rate (BER) extend the data packet to the GW. Given that, Class A devices are energy constrained, continuous overhearing of nodes and retransmissions are restricted in this scheme. Thus, minimizing the amount of energy expedition as compared to energy consumed during several retransmissions.

The rest of this paper is organized as follows. In section II we will elaborate on the related works, in section III is a detailed description of the proposed multi-hop communication based overhearing scheme, section IV performance evaluation,simulation set up, and results. Finally, section V will entail the conclusion and future work.

II. Related Works

A. Multi-Hop Communication

LoRablink [13] is one of the first multi-hop networks using LoRa. It exploits an IoT TDMA protocol designed to support reliable and energy-efficient multi hop communication. The protocol operates by combining Medium Access control (MAC) and routing, this involves the use of beacons for time synchronization which in long run creates alot of redundancy and delays. In [14] this paper proposes a minimized latency multi hop LoRa network protocol for IoT application, for reliability and low latency when transmitting the data packet. In [15], the authors present a tree-based spreading factor clustering algorithm to conduct a SF allocation in multihop network. The algorithm focuses on balancing the data traffic load in each subnet and air-time between subnets while ensuring concurrent transmissions, connectivity and coverage of LoRa networks using Multi-hop communication. In [16] a forwarding relay node and clustering approach are presented to not only enhance coverage of LoRa networks using multihop communication but also make the the system more energy efficient. In addition, this architecture forms a star of stars topology, where devices are categorized into several clusters with a motive of streamlining the operations of the network to maximize energy efficiency and consequently prolonging the network life time. Unfortunately,it the forwarding node increases the network traffic and redundancy.

B. Overhearing

Overhearing occurs when the sensor nodes listen to the medium using overhearing techniques, if the nodes overhear the neighbor's traffic they store the packets in the memory for short period of time. In [17] authors propose a communication scheme with relays to improve the reliability of a long-range sensor network with duty-cycle limitations. Herein, Class C nodes work as relay nodes to overhear sensors' transmissions and forward them to a gateway. In [11], authors made a study regarding the deployment of a programmed e-Node designed to act as a transparent range extender to overhear,store and forward to the GW all the packets from LoRa nodes. However, this scheme didn't clearly define the optimal number of e-Nodes and the placement strategy for the effectiveness of the LoRa network.

III. Implicit Multi-hop Communication scheme based on Overhearing(IMCO)

In this section, we describe a centralized scheme called IMCO which supports implicit multi-hop communications based on overhearing technique to enable the delivery of failed transmissions to the gateway in IoT LoRa communications.

A. IoT LoRa Network Model

LoRa technology is made of a star of stars topology,in which gateways relay messages between end devices and a central network server. This model is characterized by the provision of a long-range and reliable link with a special modulation technique, in which a LoRa GW(s) collects raw data directly from the end devices forwards it to a network server (NS) which is interconnected by a high-speed backhaul network, typically Ethernet or 3G as shown in Fig. 1.

B. System Model

The proposed system model emulates the conventional LoRa architecture through envisaging an implicit multi-hop communication scheme in an industrial IoT environment as a sensor field. Here proposed, provides N LoRa nodes in (Class A and B mode) with a Gaussian distribution where periodic measurements are transmitted to the Central Gateway (GW) in an interval of 30 seconds. With assumptions that all the LoRa nodes have the same level of transmission power (Tx), there no designated relay nodes and the spreading factor is allocated based on the distance from the Gateway [18] [19].

To avoid random selection algorithm of the transmission channel, IMCO scheme adopts a slotted LoRa MAC. Herein, the channel time is divided into slots with fixed length (T) and each node (N_i) with SF (s) is enabled to transmits a packet only at the beginning of a slot.

The IMCO scheme is based on overhearing technique, Owing to the broadcast nature of the wireless channel, several nodes in the locality of the sender may overhear its packet transmissions even if they are not the intended recipients of these transmissions. At the wake time the gateway selects nodes referred to as overhearing nodes(OHs) to relay packets of initially unsuccessful transmissions.

The impact of interference in the IMCO scheme is mitigated by limiting the number of retransmissions of unsuccessfully transmitted packets to the GW. This differs from the traditional LoRa where if an ACK is not received in the Rx1 and Rx2 short windows, the maximum number of retransmissions is set to 8, creates a lot of interference in the network.

Typically, an OH node is selected among the candidate set with a reliable link in terms of BER, residual energy and low SF $\in \{7, 8\}$ closer to the gateway. In this scheme, besides the direct channel allocated between the source node(S) to the Gateway (GW), we assume channels between the source node and the OH node and from the OH node to the GW. Therefore the distance parameters will be represented as follows; d_{SGW} represents one hop distance from source (s) to GW, and a two hop distance d_{SOH} between S to OH-Node and d_{OHGW} is distance from OH node to GW.

Furthermore, we suppose a set of candidate OH nodes member(OH_i) according to the requirements of the BER performance that is better than 10^{-3}. Therefore, the choice of the best OH node reliably depends on the node with the best link quality(BER) and energy efficiency to ably extend transmission of data packet for a distant node to the GW.

C. OH-Node Selection Algorithm

This section entails a chronological order in which a GW adopts a selection criterion and algorithms to pick out the best OH node from a set of active candidate nodes(OH nodes) to participate in packet forwarding and dropping off the remaining nodes with respect to Bit Error Rate (BER) and residual energy(E_r) parameters.

D. Selection of OH Candidates Zone

The initial task is to narrow down the candidate set of OH nodes for the proposed scheme, using network information obtained by the gateway from all the sensor nodes in the sensor field, the GW identifies the location position of the target node. We formulate a circular coverage also known as a forwarding Zone using a center point (O) of the radius (r) between the source node (S) and the GW. This means that all the nodes along a circle and within the circumference can participate in the selection process and can hear one another.

E. Evaluation of link reliability using BER

The average BER of the all nodes with in the circle is computed by the GW and compared with the BER threshold. That is, if a node's average BER is less than the threshold it qualifies to join the candidate set. In addition, if the link quality is above satisfaction, the residual energy of the relay node is also evaluated to confirm whether the OH node energy is not battery constrained.

In decode-and-forward, a relay node (RN) decodes the information from the received signal before its retransmission towards the destination (GW) [20] [21]. According to [22], the BER is based on SNR or E_b/N_0, applying chirp spread spectrum (CSS) as in (1).

$$BER_{CSS} = Q(\frac{\log_{12}(SF)}{\sqrt{2}}\frac{E_b}{N_0}) \tag{1}$$

In simple terms, E_b/N_0 is the ratio between the energy per bit and the noise power spectral density as in (2), while Q-function is shown in (3) [23].

$$\frac{E_b}{N_0} = \frac{P_s B}{P_n R_b(S)} \tag{2}$$

where P_s/P_n is the Signal to Noise Ratio (SNR), B is the bandwidth and $R_b(S)$ is the bit rate.

$$Q\left(z\right) = 1/\sqrt{2\Pi}\int_{z}^{+\infty} e^{\frac{u^2}{2}}du \tag{3}$$

We further make a prescriptive assumption that the spreading factor(s) used for transmission of different packets are related to distances between the source nodes to GW. If this assumption holds true, then we can establish an appropriate SF for proper calculation of BER from source to the candidate OH_i node as well as the BER from OH to the GW as shown in (4).

$$P_e(S, OH_i) = Q(\frac{\log_{12}(SF_i)}{\sqrt{2}} \times SNR \times \frac{2^{SF_i}}{SF_i}) \tag{4}$$

F. Evaluation of nodes' Residual Energy

The nodes' residual energy (E_{re}) is a substantial determinant for a node to complete data transfer without interruption. When the residual energy of the node exceeds a predetermined energy threshold, it remains in the candidate set of OH nodes. The residual energy of the candidate OH node is computed by (5).

$$E_{OH_i,re} = E_0 - E_{(OH_i,total)} \tag{5}$$

$$E_{(OH_i,total)} = E_t + E_r + E_{ov} \tag{6}$$

Where, $E_{OH_i,re}$ is the residual energy of the OH node, E_0 is the initial energy, $E_{(OH_i,total)}$ is total energy which incorporates transmission (E_t), received (E_r) and overhearing (E_{ov}) operation energy consumption. Considering all the nodes within and along the selected circumference as a candidate set of OH nodes, the next phase is to elect the energy threshold (E_{th}), given the GW having information about the candidate set for an effective evaluation process. Firstly, we compute the total residual energy $E_{re}(t)$ of the candidate nodes at a particular time (t) is given by (7).

$$E_{re}(t) = \sum_{i=1}^{N} E_{(OH_i,re)} \tag{7}$$

Where, N is the number of candidate nodes in the selected area.

Secondly, The average residual energy $\overline{E_{re}(t)}$ for each node is defined as (8).

$$\overline{E_{re}(t)} = \frac{E_{re}(t)}{N} \tag{8}$$

Where, $\overline{E_{re}(t)}$ is the average residual energy.

Therefore, we can deduce that the energy threshold E_{th} is considered to be the average residual energy ($\overline{E_{re}(t)}$) of the candidate set of OH nodes. Wherein, $E_{OH_i,re} > E_{th}$ is the condition considered for all nodes to qualify for the the last phase of the electing of the best OH node with in the forwarding area.

G. Selection of the Best OH Node

The node OH_i with the highest rank (R(i)) becomes the best OH node and the rest of the nodes serve in the next cycle. The normalized values of both link quality in terms of BER and residual energy are computed. The OH node with the highest rank computed as in (9) and (10).

$$R(i) = \alpha \frac{L(i) - L_{min}}{L_{max} - L_{min}} + (1 - \alpha) \frac{E(i) - E_{min}}{E_{max} - E_{min}} \tag{9}$$

Where, $L(i) = P_e(i)$, $L(i)$ is the desired link quality in terms of Bit Error Rate, $R(i)$ the ranks of candidate nodes, $E(i)$ is residual energy. The BER with the ratio α and residual energy with the ratio $1 - \alpha$ for $\alpha \in [0, 1]$.

$$OH^* = \arg\max_{i \epsilon N}(R(i)) \tag{10}$$

Where, OH^* is the OH node with the optimal value of $R(i)$ is selected as the best OH node to implicitly transmit data to the GW. However, in case of any failure of an optimal OH node (Highest rank R(i)) to overhear the source node data packet, the timer for second-ranked node using the R(i) value will time out so that it can overhear and extend the overheard data packet to the GW. The rest of the remaining nodes in the candidate set cancel their timers after overhearing a response.

H. OH Nodes Back Off

As soon as the selected OH node has successfully transmitted an overheard data packet to the gateway during a transmit window, the rest of the candidate nodes have to halt their transmission of the overheard messages. This can be achieved through the use of a Back-Off-based strategy, in which a Back-Off timer is mapped to all the nodes to their ranks (R(i)) in the forwarding zone. In simple terms, the Back-Off timer is tuned in such a way that the best OH node with the optimal value is prioritized with a smaller Back-Off time. OH_i will start its timer with an initial value T_i inversely proportional to the combination of link quality and residual energy (R(i)) according to (11).

$$T_i = \frac{\rho}{R(i)} \tag{11}$$

Here, ρ is a constant, the units of ρ depends on the units of both Link quality and Residual energy, ρ takes the units of time (microseconds).

IV. Performance Evaluation

In this section, we first describe our simulation environment, model and performance evaluation metrics. We compare the performance of IMCO scheme with the two existing approaches categorized in implicit multihop based on an enhanced LoRawan node as known as e-Node scheme [11] and explicit multi-hop scheme [16]. Finally, we evaluate the performance of the proposed scheme in comparison to the previous communication schemes through simulation results.

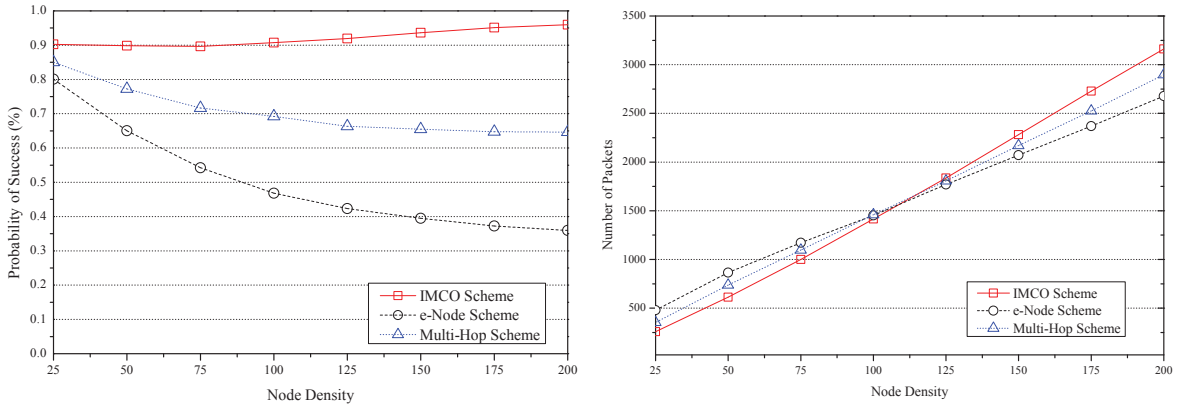
A. Simulation Environment

We used NS-3 simulation environment to model multi-hop in LoRa network through the overhearing mechanism of selected sensors to extend packets to the Gateway in contrast to the performance of the e-Node scheme and the multi-hop scheme based on an enhanced LoRaWAN node.

In our simulation model a number parameter were used. Where the size of the network field is an area of 15,000 meters. Each node transmits a packet of size 30 byte on average $t = 30$ seconds per 24 hours, the estimated transmit power is 14 (dBm) for all the nodes, the channel bandwidth is $125 \leq BW \leq 500$ KHz, and a channel code rate of 4/5, protected by a cyclic redundancy check (CRC) with a 1% duty cycle restriction. We simulate a network topology containing varying N stationary LoRa nodes with a Gaussian distribution in concentric circles with a gateway located at the center of the sensor area to ensure a maximum coverage range.

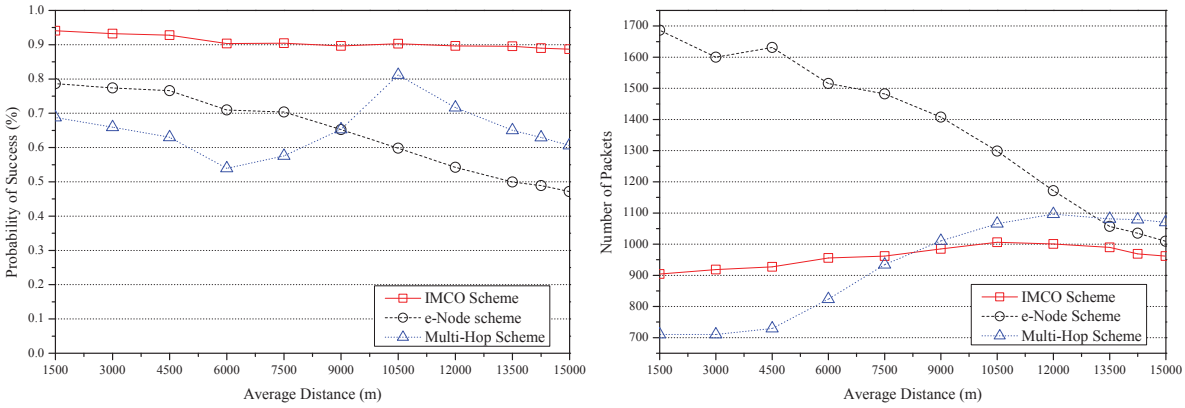
For comparison purposes, we consider two existing schemes [11] and [16] to discover the differences between them and also ascertain the relevance of our proposed scheme based on the performance metrics, of which they are categorized into either implicit or explicit multi-hop communication. The metrics used for performance evaluation of the proposed scheme are:

- Probability of Successful Transmission
  To derive the probability of successful transmission P_{suc} of a frame as in (12).
  $$p_{suc(i)} = e^{-2 \times N_{sf(i)} \times D} \ \ with \ 0 \leq P_{suc} \leq 1 \tag{12}$$
  where $N_{sf(i)}$ is the density of nodes within a given $SF(i) \epsilon \{7 \sim 12\}$ and D represents the duty cycle.
- Number of Packets
  The number of packets traversing the network to the GW is a vital parameter as far as understanding of the traffic behavior for either congested or uncongested communication in LoRa network is concerned.



(a) (b)

Fig. 2. Plots of the performance evaluation metrics : The Probability of Success and Number of Packets against Node Density of various schemes (**a**) the Probability of Success as a function of Node Density and (**b**) Number of Packets as a function of Node Density.



(a) (b)

Fig. 3. Plots variation in Average Distance with Probability of Success and Number of Packets for various schemes: (**a**)Probability of Success vs Average Distance and (**b**) Number of Packets vs Average Distance .

B. Simulation Results

In this section, we present the obtained results of the performance evaluation metrics using LoRa nodes communication transmission parameters, we compare the performance of IMCO scheme against the two distinct multi-hop comparing schemes; An implicit e-Node Scheme with an enhanced LoRa and an explicit multi hop scheme for range extension using relay nodes respectively.

The variations in node density with the probability of success and number of packets of the three LoRa communication schemes are investigated in this study. The results show in Fig. 2(a) a decrease in the probability of success with an increase in node density for the e-Node and Multi-hop Schemes. This reduction could be attributed to the ALOHA media access strategy which causes collisions derived from the blind transmission strategy. However, the probability of success in the IMCO scheme remains constant with 100 nodes deployed in the network and a significant raise to approximately 96% with increasing node density of up to 200 nodes was observed. This increase could be ascribed to the involvement of relays with better BER and use of the overhearing strategy.

There is a direct proportionality between the number of packets transmitted and the node density of all schemes Fig. 2(b). The number of packets increases with an increase in the number of nodes. We observe that the IMCO scheme initially registered a relatively low number of packets against the node density with 100 nodes deployed and thereafter a slight increase in the number of packets surpassing the e-Node scheme and multi-hop scheme. Therefore, having a sizeable number of OH nodes with fairly good link quality offers efficient retransmission in case of transmission failure of the source node. Consequently, a gradual rise in the number of packets as the

number of nodes increase is justified. Contrary, the e-Node scheme and multi-hop scheme at this point are susceptible to poor link quality, collisions, and channel contention resulting in a drop in the number of packets transmitted.

Fig. 3 show the variations in the average distance with the probability of success and number of packets. In general, there is a decrease in the probability of success with average distances for all the schemes as shown in Fig.3(a). This is attributed path loss, where messages sent by LoRa nodes that are furthest from the GW experience the highest Packet Loss Ratio (PLR) and longer Time on Air (TOA). Secondly, This decrease is an effect of the ALOHA media access strategy which causes collisions derived from the blind transmission strategy [24] [25]. The findings further show that IMCO scheme exhibits the best performance over 89% along with various average distances from the GW. This could be due to the significant increase of the OH nodes that retransmit all the failed transmissions to the GW. Indeed, bridges the gap of unsuccessful transmissions.

In Fig. 3(b), the IMCO scheme has a relatively stable and least amount of packets transmitted compared to the e-Node and the multi-hop schemes. Precisely, the e-Node scheme exhibits the highest number of packets due to the implementation mechanism where the e-Node replicates all packets transmitted by source nodes and forwards them to the GW. However, as the average distance increases the e-Node scheme depicts an ameliorated performance. Unlike the multi-hop scheme number of packets as the average distance increases. This occurs as a result of relays located closer to the distant nodes extending packets from the source to the GW.

V. Conclusion and Future work

To achieve a high packet delivery success ratio, this paper presents a novel IMCO scheme for IoT services in LoRa based LPWAN faced with limited connectivity. The IMCO scheme utilizes implicit relay nodes to carry out overhearing operations. The proposed scheme considers the selection of OH candidate zone, evaluates the average BER and residual energy of the node as the selection strategy of the best OH node, with a backoff-based strategy to eliminate collision of packets for simultaneous transmission attempts. In general, our analytical results indicated that the use of overhearing strategy significantly increase the probability of success in the sensor network. The IMCO scheme still outperforms the e-Node scheme and multi-hop scheme by achieving the highest probability of success. As future work, this scheme will be extended to a systematic priority-based Adaptive data rate for LoRa multi-hop communication.

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