Improving 6TiSCH Reliability and Latency with Simultaneous Multi-Band Operation

Marcus Vinicius Bunn, Richard Demo Souza, Samuel Baraldi Mafra, Guilherme Luiz Moritz

***Abstract*— The Internet Engineering Task Force (IETF) group "IPv6 over the TSCH mode of IEEE 802.15.4e" (6TiSCH) introduced a protocol, utilizing Time-Slotted Channel Hopping (TSCH) from IEEE802.15.4e, that achieves industrial performance requirements while offering the benefits of IP connectivity. This work proposes the addition of a second radio interface in 6TiSCH devices to operate a parallel network in sub-GHz, introducing transmit diversity while benefiting from reduced path-loss and interference. Simulation results show an improvement of 25% in Packet Delivery Ratio (PDR) and around 30% in latency in different network scenarios.**

***Keywords*— Industrial IoT, Multi-band, sub-GHz, 6TiSCH**

I. INTRODUCTION

Industrial Internet of Things (IIoT) [1], one of the Industry 4.0 paradigms, aims to enhance factory connectivity levels in order to increase productivity. A major challenge is to guarantee the communication requirements in terms of determinism, latency and reliability required by critical industrial applications [2]. To address this issue, Time-Slotted Channel Hopping (TSCH) mode of IEEE802.15.4e [3] has been designed. By delivering 99.999% end-to-end reliability and over a decade of battery lifetime [4], TSCH has become the *de-facto* Medium Access Control (MAC) technique for industrial applications. On top of TSCH MAC, the Internet Engineering Task Force (IETF) group "IPv6 over the TSCH mode of IEEE 802.15.4e" (6TiSCH) specified a communication stack capable of meeting industrial performance requirements while offering the benefits of IPv6 connectivity [5].

TSCH is based on a robust design, but the continuous increase in connected devices combined with the strict reliability and latency requirements of the Industry 4.0 paradigm pose new challenges. Therefore, existing and continuous efforts from the industry and academia are required to improve IIoT networks performance. Some related work aim at improving TSCH via redundant transmissions [6], [7] and the usage of sub-GHz band with multi-band support [8], [9]. However, it is noticeable the absence of a single approach that combines both methods, and which can improve TSCH network performance against interference and multi-path fading. In this context, this work proposes the addition of a second radio interface in 6TiSCH devices to operate a parallel network in sub-GHz band, which increases the network reliability, latency, and connectivity by introducing transmission diversity while benefiting from decreased path-loss propagation and reduced interference from other technologies. The results of several simulations show potential improvements of up to 25% in Packet Delivery Ratio (PDR) and closely to 30% in latency in different tests, at the cost of increased hardware complexity.

II. 6TISCH OVERVIEW

The (6TiSCH) stack uses the IEEE802.15.4 physical layer (PHY) operating in the 2.4 GHz (ISM) band. This band is divided in 16 channels [3] whose use is governed by the TSCH IEEE802.15.4e mode, which combines Time Division Multiple Access (TDMA) with channel hopping. Additionally, 6TiSCH provides a set of management protocols that enables plug-and-play bootstrap, authentication and wireless medium management [10].In the 6TiSCH stack, communication occurs in specific times while obeying a maximum duration determined by a *timeslot*. Timeslots repeat in time indefinitely and a group of timeslots is named a *slotframe*. A scheduling function determines whether a node is transmitting, receiving or sleeping in each timeslot, which can offer deterministic and reliable communication with improved battery lifetime by allowing nodes that are not transmitting or receiving to enter in sleep mode. The resulting allocation, named schedule, can be viewed as a repeating $M \times N$ matrix, where M is the number of available physical channels and N is the slotframe length. Channel hopping is achieved by selecting offsetting channel cells in each slotframe iteration [10].

To provide a zero configurarion network, the 6TiSCH minimal configuration [11] defines a mandatory basic schedule which must be followed by any 6TiSCH node. This minimal schedule provides basic message exchange that can be used in conjunction with the 6TiSCH Operation Sublayer (6top) Protocol (6P)[12] to negotiate more complex communication schedules governed by a Scheduling Function (SF). A mandatory basic Schedule function, named Minimal Scheduling Function (MSF) [13] is provided by 6TiSCH. After single link communication is established, RPL [14] protocol is used to create a routing topology where each node communicates only through a parent node that is chosen upon joining process. Additionally, an already joined node can also act as parent for other nodes. These rules give rise to a multihop tree-like structure named Directed Acyclic Graph (DAG). If the parent is not the actual destination of a message, it is sent upwards until it reaches the first node of topology, called DAG Root. This node have complete knowledge of the DAG structure and can send the message to the destination. The upper layers of 6TiSCH are beyond the scope of this letter and are detailed in [10].

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III. RELATED WORK

This section discusses related work that use the TSCH mode of IEEE 802.15.4e and that propose redundant transmission, sub-GHz operation and multi-band support.

Minet et al. [6] exploit redundant transmissions that benefit from different communication links to increase reliability, where a node sends a message through multiple paths depending on a redundancy pattern. The sink node accepts the first delivered message and discards the late copies, which increases reliability and reduces latency. The increase in reliability is achieved at the cost of additional network overhead that decreases battery lifetime. Moreover, additional studies would be required to confirm the effectiveness of the proposed strategy on interference prone environments with coexisting networks, where redundant transmissions could degrade performance by increasing network density and interference levels.

Papadopoulos et al. [7] propose redundant transmissions associated with an overhearing mechanism to increase reliability and reduce latency. Each node forwards its messages not only to the default RPL parent but also to a redundant parent. In addition, packet retransmissions due to incorrect receptions are eliminated. Simulation results were compared against the default TSCH-RPL network using different retransmission levels, demonstrating a reduction of up to 54% in end-to-end latency and 84% in jitter when compared with a non redundant scenario with 8 retransmissions at the cost of increased energy consumption caused by the redundant transmissions. Regarding PDR, results showed no improvements when compared to the the retransmission approaches, and the authors justify this behavior by stating that the removal of retransmissions negatively impacted the control packets reliability.

Yin, et al. [8] tackles the interference problem on WSNs that operate in the 2.4 GHz band caused by popular WiFi and Bluetooth network deployments by proposing dual band operation. The scheme performs sequential transmissions for both 900 MHz and 2.4 GHz. Experiments were conducted to evaluate the proposed scheme performance on two different testbeds [15], [16]. The PDR is selected as evaluation metric and tests are executed over varied wireless channels from 900 Mhz to 2.4 GHz. Results show that the average PDR was approximately 5% higher in the 900Mhz band, while also improving the connectivity by 15%, when compared to the 2.4 GHz band. It concludes, based on experimental results, that the presented scheme can be used to increase network performance and connectivity, although the paper focuses only on the physical/link layers.

Brachmann, et al. [9] propose multiple frequency and bitrates in a single IEEE 802.15.4e TSCH schedule to meet multiple application requirements by trading datarate with robustness. Two approaches are investigated, the first assigning timeslots duration to accommodate the slowest transmission and the second allowing slower transmissions to use several timeslots. The performance of the proposed schemes were evaluated experimentally using 25 nodes deployed in an office environment. For the tests, TSCH control data was transmitted in the sub-GHz band that offer increased reliability while application data is transmitted over 2.4 GHz to achieve faster delivery times. The usage of sub-GHz bands granted single-hop reaches close to 24 nodes at 1.2kbps, while at the standard 250kbps in 2.4 GHz the reach decreases drastically to an average of 10 nodes. Results also showed that the 1.2 kbps band at sub-Ghz has a 20x higher channel utilization when compared to the 2.4GHz band at 1000 kbps, while improving network synchronization by reducing the required average hops for control data. The work successfully demonstrates the required timing configuration required in TSCH networks to operate in sub-GHz and allows multi-band operation.

Van Leemput et al. [17] proposed a multi-phy TSCH network where the rate of the unicast links is lowered when the average of the Received Signal Strength Indicator (RSSI) drops below a preconfigured threshold. To accommodate the slower PHYs, the author breaks compatibility with the 802.15.4e standard by allowing a node to transmit more than one packet on a timeslot. This way, the network can be configured to use a long enough timeslot to allow a slower PHYs transmission and acknowledgment reception without the bandwidth penalty that would be imposed to the faster PHYs if only one transmission per slot were used. Using this scheme, the authors claim a throughput increase of 153%.

A similar link-by-link PHY switching basis is evaluated in [18], where it is stated that their technique allows the radio to use a more energy efficient interface when possible, switching to a more reliable but more power hungry when needed. Results show that the strategy yields lower latency and network formation time than any of the individual used PHYs. On the other hand, the solution is not compatible with the IETF 6TiSCH specification.

Against the above background, we propose the simultaneous use of multi-band interfaces. Our solution utilizes 2.4 GHz and sub-GHz networks like [7], [8], [9], but we apply redundant transmissions and exploit diversity in a more "standard" fashion, where redundancy occurs naturally by using the additional operating band combined with frequency and spatial diversity associated with the different TSCH and RPL networks. Our method is simpler to implement than [18], since no modifications to the communication stack are required. As an additional advantage, the proposed method allow multiband nodes to communicate with single band devices from any of the supported PHYs, which allows the deployment of a hybrid network where the less energy efficient and more complex multiband nodes are used only when needed, seamlessly communicating with single band devices.

IV. PROPOSED CONFIGURATION

This work proposes multi-band support in 6TiSCH by employing two independent radio interfaces with concurrent transmissions, as depicted in Figure 1. The 2.4GHz band uses the IEEE 802.15.4e PHY specification with 16 channels, each spaced by 5MHz, and transmits at 250kbps rate. At this rate, within a 10ms TSCH timeslot it is possible to transmit a data frame and to receive an acknowledgment [9]. The sub-GHz band follows the IEEE 802.15.4g-2012 standard [19] configuration using the Operating Mode #1 for the 863-870MHz band in Europe which is specified for 50kbps transmission rate and

200kHz channel spacing in a total of 34 available channels. Due to the slower transmission rate, the timeslot timing must be adapted. Then, since there is no standard value in the IEEE specification, we elected 29.38ms as in [9, Table III], mainly because of their proven efficiency and thorough tests.

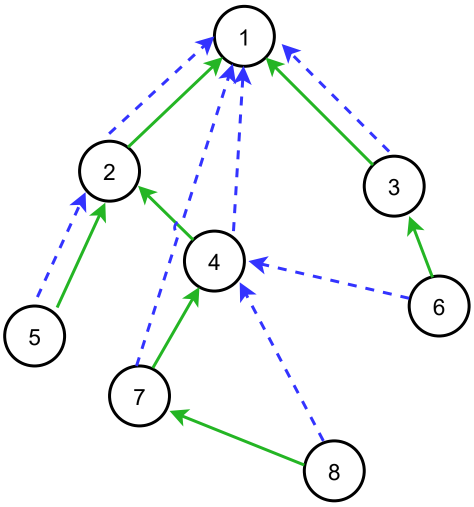

Fig. 1. Multiband operation proposed in this work. Two single band network topologies, one operating in the 868MHz band (blue dashed lines) and other operating in the 2.4GHz band (green solid lines) can be combined to form a multiband topology where each transmitter packet experience diversity effects by being transmitted simultaneously in both bands using two different paths. Results show that multiband operation can significantly improve packet delivery ratio and latency when compared with the single band networks.

The two interfaces can be exploited in at least two approaches. The first is by means of a common topology where a node chooses the transmitting band in a per hop fashion. The second is by forming an independent routing topology for each band, and then, when a packet is generated, scheduling it for transmission in both interfaces as soon as possible. The actual transmit time may be different for each interface due to the independence between timeslot duration and scheduling configurations in different bands. Using a common topology is more energy efficient, but imposes some disadvantages. The first one is the fact that dual band operation is not supported by the 6TiSCH specification, which breaks compatibility of each node running the dual band stack. In addition, routing algorithms in dual band mode are more complex, which may be undesirable in resource constrained nodes. Finally, since the packet is only sent using one interface, there is no diversity benefit from multiple paths. For this reason, this work uses the dual topology strategy, where each message traverses two routing paths. By using diverse paths to the DAG root, we envision that it is possible to improve the overall performance in terms of PDR and latency simultaneously due to the introduction of frequency diversity, reduced interference and increased robustness. As a drawback, in our proposal packets may arrive in duplication at the destination. For this reason, a simple algorithm is required at the network sink for discarding replicas.

V. EXPERIMENTAL RESULTS

The 6TiSCH Simulator [20] was used for experimental results. In addition to the default TSCH configuration for the 2.4GHz operating band based on OpenMote [21] already available, a second sub-GHz configuration was added, based on the Texas Instruments CC1352R [22] radio operating in the 802.15.4g SUN PHY at 868MHz. For the linear topology the nodes were uniformly distributed in a 100m × 100m square, this way the distance between nodes varies from approximately 8.3 meters on 160 node topology to 16.6 meters on 40 node topology. In the random topology, as the name implies, node placement is random, with an average distance which is equal from the linear topology. There is a 5400 second network formation time where statistics are not collected and from this point 7200 seconds are simulated. Propagation is based on the Pister-Hack model. The packet reception probability is defined as a table mapping in function of RSSI values. This table was obtained empirically in a real deployment utilizing the OpenMote devices [23], accurately reflecting the relationship between RSSI and PDR in large indoor industrial scenarios at the 2.4GHz band. For the 868 MHz band, the same table was used, but a 13 dB margin is applied regarding the difference from the Texas Instruments CC2538 radio [24] sensitivity used in [23] to that of the Texas Instruments CC1352R which would be used for a similar test in the 868 MHz band.

To evaluate the obtained performance, a simulation scenario with 2 different bands of operation and 12 topologies were implemented. Network topologies are formed by 3 different network sizes $N \in \{40, 80, 160\}$, and 2 deployment models, namely Linear and Random. The DAG root is always positioned at the center and all nodes must have at least one reachable neighbor. Two metrics were evaluated, the first one is the PDR, calculated as the ratio between the number of messages that has reached the destination by the overall number of messages that were generated. The second metric is the latency, calculated as the time elapsed between a message being generated and its arrival at any of the destination interfaces. Each node generates a 90 byte message with an interval T_a equal to 10 seconds and transmits them to the DAG root using both interfaces, abiding by each band TSCH scheduling and RPL configuration. MSF determines when communication occurs for each node to its neighbor at every hop. If no cells are available for one node to communicate with its neighbor, the transmission is scheduled for the next slotframe, where MSF controls if additional communication timeslots are required. For the 2.4GHz and 868MHz runs, the nodes only transmit using the appropriate frequency, for the multiband test, each generated packet is transmitted in both bands, as soon as a suitable slot is available.

We initiate our discussions by first presenting results concerning the PDR for each combination of network size, operating band and deployment in Figures 2 and 3. In addition to that, the associated joint metric resulted from the combination of both interfaces is also presented. It can be noticed that the PDR decreases with the network size, effect that is most significantly observed in the 2.4Ghz band. The network size increase also degrades the joint metric results from multi-band support, yet the proposed configuration still considerably improves the overall performance. The most significant improvement is observed in the Linear deployment with 160 devices as demonstrated in Figure 3. There, multi-band support improved PDR by 20% when compared to the single usage of 2.4GHz and close to 7% when compared to the single usage of 868MHz band. Similarly, multi-band support offered an increase of 4.84% and 7.09% in the PDR for the 40 and 80 network sizes using Linear deployments.

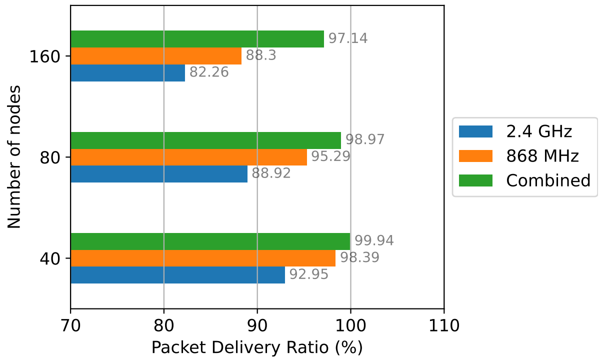

Fig. 2. PDR results for each operating band varying in network size with 40, 80 and 160 nodes deployed in a 100m × 100m area, in the random topology.

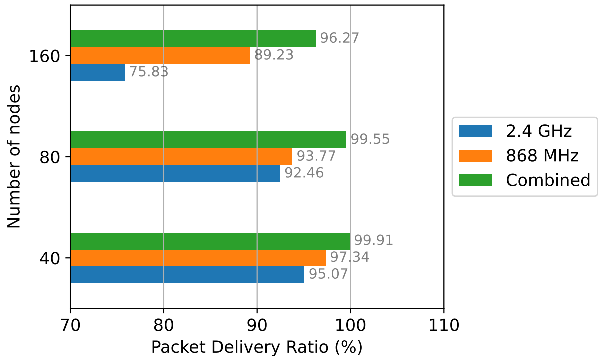

Fig. 3. PDR results for each operating band varying in network size with 40, 80 and 160 nodes deployed in a 100m × 100m area, in the linear topology

Regarding Random deployments, in most cases the same behavior was observed. The increase in network size resulted in lower network performance, while the multi-band support yielded significant improvements of 14.88% for the 160 node network, 10.05% and 6.99% for 80 and 40 node network, respectively.

Moreover, the reason for decreased performance over larger networks is that the more denser the network, the higher is the interference and the strain over bottlenecks nodes closer to the DAG root [25]. This loss in performance is most noticeable in 2.4GHz operating bands mainly due to its weaker sensitivity.

A. Latency

In terms of latency, similarly to the case of PDR, the increase in network size resulted in poorer overall network performance, while the multi-band support yielded significant improvements. Figures 4 and 5 present the average latency for each operating band and the resulting joint metric in case of multi-band support. It can be noticed an improvement of 30.76% and 16.6% in the average latency by combining both operating bands when deploying Linear networks of size 40 and 80, respectively. Similar behavior was observed in the Random deployment, obtaining an improvement of 24.33% and 16.04% in the average latency with 40 and 80 nodes. This benefit is associated with reduced packet retransmissions and reduced average hop number in packet forwarding.

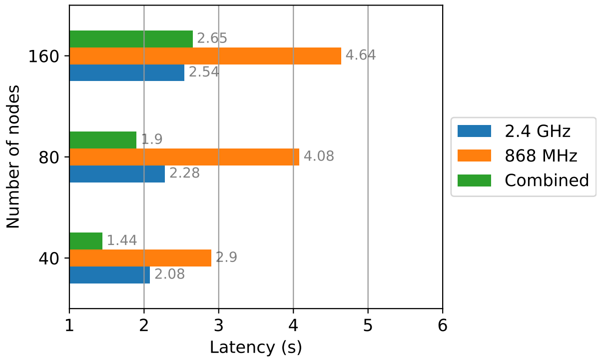

Fig. 4. Average latency results for each operating band varying in network size with 40, 80 and 160 nodes deployed in a 100m × 100m area, in the linear topology.

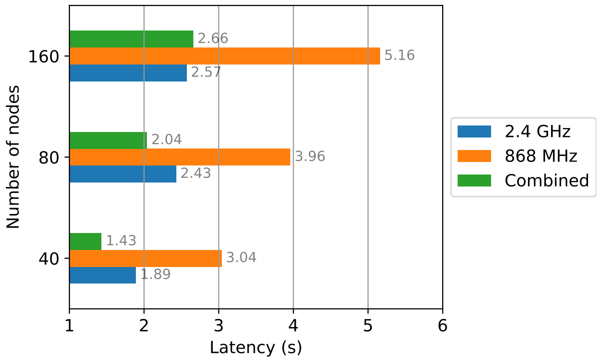

Fig. 5. Average latency results for each operating band varying in network size with 40, 80 and 160 nodes deployed in a 100m × 100m area, in the random topology

However, as shown in Figure 4, one can observe a 4.33% degradation in the average latency for the joint metric when compared to the 2.4 GHz band in the 160 nodes scenario. This can be explained by the PDR reduction caused by the density increase of the network.

From Figures 3 to 5 we can observe that, for the 868 MHz interface, the average latency and the PDR are always higher than those considering the 2.4 GHz interface. On the other hand, since both the combined latency and combined PDR could be reduced for the 40 and 80 motes topologies, we can infer that eventually some packets are delivered faster by the

868 MHz interface than the 2.4 GHz interface. Although that may sound counterintuitive, it may be due to some packets that were transmitted in less hops in the 868 MHz interface than they would be in the 2.4 GHz interface, or because the 868 MHz required less retries due to its increased PDR. However, clearly, the 2.4 GHz interface contributes more to the good latency results than the 868 MHz interface. Nevertheless, in more demanding conditions, as in the case of the 160 nodes topology, the 2.4GHz network starts lowering its contribution to the overall metrics, and we observe a tendency of the numbers to drift towards the 868MHz typical performance. With a PDR of approximately 76% in the 160 motes topology, the 2.4 GHz interface is not able to contribute to reduce the average latency, as almost 24% of the packets would be delivered exclusively by the 868 MHz interface, which is typically slower.

While the increase in average latency can appear to be harmful to the network, the increase in successfully received packets offered by combining both bands is essential to the correct execution of certain applications, thus representing an appealing trade-off.

VI. CONCLUSION

This work proposed the addition of a second radio interface in network devices to operate a redundant 6TiSCH network in sub-GHz bands. The experiments showed that multi-band support is beneficial for 6TiSCH networks and various industrial applications by providing frequency diversity and reducing interference from other technologies, thus increasing PDR. Also, multi-band support is useful in decreasing average packet retransmissions, hence allowing lower end-to-end latency in most cases. Regarding latency, it can be noted that duplicated packets have different propagation channels and face distinct routing paths as a consequence of the different DAGs for each band. Single hop transmissions in the 2.4 GHz band offer the fastest transmission time, as a consequence to its higher transmission rate and shorter slotframe duration. On the other hand, due to its lower robustness and shorter range, 2.4GHz interfaces have a greater chance of requiring retransmissions or a higher number of hops to reach the destination.

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