5G-Wi-SUN for Building Management System

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***Abstract*—With higher data rates and lower latency, 5G constitutes a mobile alternative to both wired networks and less capable wireless solutions. However, the performance of 5G requires expensive hardware and high energy consumption, making it less suitable for energy-constrained edge devices. Combining the capabilities of 5G for Wide Area Network (WAN) access, with the benefits of other wireless networks purpose-built for low-power embedded systems, a Building Management System (BMS) based on 5G can be deployed anywhere in a building with 5G coverage extended with a suitable LPWAN connectivity for IoT devices of the BMS. In this paper, the LPWAN of choice is the Wireless Smart Utility Network (Wi-SUN), a low-power sub-GHz connectivity based on IEEE 802.15.4g, offering mesh and multi-hop features for improved reliability and range, alongside competitive data rates. The performance of a 5G-Wi-SUN hybrid network was evaluated with a fibre-broadband hybrid network, a 5G-only network and a Wi-SUN-only network to determine the feasibility of 5G-Wi-SUN network. Test results show a significant performance of our 5G-WiSUN network, with a round-trip times below half a second in most cases, and a trimean of 115ms, only 27ms more than the fibre broadband-WiSUN network in our experiment. Consequently, the results have demonstrated the ability of a 5G-Wi-SUN network to provide a versatile alternative to fibre broadband-WiSUN, while maintaining a comparable performance.**

***Index Terms*—5G, Wi-SUN FAN, Internet-of-Things, Low-power Wide Area Network**

I. INTRODUCTION

Recent advances in cellular technology have resulted in mobile connectivity with ever-improving capabilities. The 5th-generation of Mobile Telephony (5G) New Radio (NR), defined by the 3rd Generation Partnership Project (3GPP) is built revolving around its core concepts of Enhanced Mobile Broadband (eMBB), Ultra-Reliable and Low-Latency Communications (URLLC), and Massive Machine-Type Communications (mMTC) [1]. The unprecedented mobile bandwidth provided by eMBB has opened up cellular systems to high-bandwidth applications while supporting mobility, such as on-the-go video streaming. URLLC on the other hand offers much reduced latency and improved reliability, thus making cellular networks suitable for safety-critical applications with low latency requirements. Furthermore, the introduction of Internet-of-Things (IoT) has greatly increased the density of networked devices and 5G mMTC aims to support huge capacities of user equipment.

A Building Management System (BMS) is used to control and monitor various aspects of a building's functionality and performance, such as heating, ventilation, air conditioning, lighting, security, and energy consumption. Many buildings are now equipped with IoT sensors and actuators, providing continuous monitoring and automation to optimise the building's efficiency, comfort, safety, and sustainability. Increasingly, wireless connectivity is being deployed in BMS to interconnect the IoT devices. Many IT departments view IoT devices as non-security-compliant network components that should be separated from the corporate IT network [2]. This is necessary to prevent intrusion into the IT network through vulnerable IoT devices of the BMS.

However, as enticing the performance and convenience of 5G may seem, it would be costly to equip every device in the building with 5G connectivity. 5G connectivity is not optimised for energy-constrained devices such as battery-operated embedded systems, while high hardware costs of the 5G modems present an additional challenge to equipping any device with 5G. In addition, BMS devices often do not require the multi-gigabit high bandwidth that 5G modems are capable of. As a countermeasure, we advocate that 5G can be used with other mesh connectivity for optimal cost and operational needs. With downlink speeds exceeding 300 Mbps and uplink speeds of 30 Mbps [3], 5G can enable Wide Area Network (WAN) access without the need for any new infrastructure such as optical cables. There already exist a number of 5G Consumer Premise Equipment (CPE), often equipped with some from of Local Area Network (LAN) connectivity such as Wi-Fi so local devices can share the 5G WAN bandwidth. It is foreseeable that 5G will not be replacing most of the existing connectivity protocols, instead it will augment with the well-known protocols to enhance the service offerings, thus optimising bandwidth, system operations and improving system and data security.

In this paper, we propose a novel approach to extend the low latency, high bandwidth features in the last mile connectivity by inter-connecting a 5G network with Wireless Smart Utility Network (Wi-SUN), deployed in a building. As compared to other wireless networks such as LoRA, Wi-Fi and NB-IoT, Wi-SUN has a competitive edge: in addition to low power consumption, it offers lower latency, and higher bandwidth

TABLE I
Comparison of the characteristics of Wi-SUN, LoRaWAN and NB-IoT [4] [5] [6]

Parameters	Wi-SUN	LoRaWAN	NB-IoT
Frequency	<Unlicensed Sub-GHz	863 to 870 MHz, 902 to 928 MHz, 779 to 787 MHz ISM Bands	700MHz, 800MHz, 900MHz, 1700MHz, 1800MHz and 1900MHz
Data rate	Up to 300 Kbps	0.3 to 22 Kbps (LoRA modulation) and 100 Kbps (using GFSK)	Up to 60 Kbps in Cat NB1 and up to 158 Kbps in cat NB2
Latency	0.02 to 1 sec	1 to 2 sec	1.4 to 10 sec
Coverage range	4 km point to point using 1W output from non directional antenna	2-5km (urban areas), 15km (suburban areas)	1km (urban), 10km (rural)
Current consumption	2μA (while at rest), approx. 8mA (listening), <14mA at +10 dBm (transmission)	2 to 3 μA (at rest), 12 mA (listening) approx. 26 mA (+2 dBm transmit)	2 to 3 μA (sleep) 40 mA (listening) 120 to 300 mA (+23 dBm transmit)
Preferred application	Frequent communication up to 10 seconds	Infrequent communication up to 128 seconds	Infrequent communication up to 600+ seconds

to support modern fast changing wireless communication environments. Additionally, Wi-SUN mesh-networking allows for a more effective expansion of connectivity coverage in the building. Sensors and actuators are attached to the Wi-SUN network and the Wi-SUN Border Router serves as the 5G gateway. Thus, near real-time sensor data in the building can be aggregated within the Wi-SUN network before being sent to the cloud to perform real-time predictive analytics. Being a mesh network solution, Wi-SUN Field Area Network (FAN) is also a suitable complementary technology to increase scalability in a large-scale star network such as a 5G IoT network. The inter-networks can be further scaled up by adding Border Routers to the network. Such an architecture can significantly increase the scalability and flexibility of the 5G-Wi-SUN internetwork in accordance to different application requirements.

The paper is organised as follows: Section II presents related hybrid connectivity network and some background on Wi-SUN, LoRA and NB-IoT. Section III describes the proposed 5G-Wi-SUN network for building management and presents the prototype implementation. Section IV shows the preliminary results of the 5G-Wi-SUN performance, and Section V concludes the paper with future work.

II. Related Work

A well-known example of a hybrid network involving 5G is Wi-Fi. While 5G and Wi-Fi can have overlapping use cases, especially in indoor scenarios [7], it is still viable to have a hybrid 5G with Wi-Fi network where the strengths of both networks complement each other. 5G is designed for a wide coverage and superior mobility, which offers reliable connectivity to an Internet Service Provider (ISP), and subsequently the Internet. However, its deployment is hampered by high costs of 5G modems and potential subscription costs when using 5G with a mobile carrier. The network can be augmented with Wi-Fi, which is much cheaper and easier to deploy, and is already commonplace amongst smart devices [8]. This is made evident by the wide availability of 5G CPE with Wi-Fi access. [9] also highlighted several scenarios for a private 5G network and Wi-Fi network to coexist, providing access to backend servers simultaneously, wherein high mobility devices can take advantage of the 5G network, and Wi-Fi only devices can still access the servers through Wi-Fi.

One rising topic with the introduction of 5G is 5G positioning. With enhancements such as increased frequency bandwidth and beamforming, positioning with cellular networks has been highly improved [10]. 5G positioning can be combined with traditional positioning systems, such as satellite navigation systems to further improve the latency and accuracy of position data [11].

Several implementations of LoRa in indoor environment [12]–[14] have shown that long range communication protocol is more suitable to manage sensors and actuators in a building, as compared to short-range communication protocols such as Zigbee, Bluetooth and other 2.4 GHz technologies [15]. LoRa's gateway in particular supports concurrent communication of multiple nodes hence enabling the deployment of a scalable LoRaWAN network in a building. Additionally, LoRa has low energy usage during transmission. However, a trade-off observed is that it appears to be difficult to use LoRa to transmit a significant volume of sensory data of smart buildings to the cloud due to the low data rate of LoRa. Furthermore, using the unlicensed frequency bands by a large number of LoRa nodes has resulted in the interference, which exacerbates the network performance. Though approaches such as using multiple gateways, scheduling of nodes to transmit data in a given period could be employed to reduce the interference, this has resulted in higher network cost and the reduction of gateway utility respectively [16]. Observations were made that LoRa also performs quite poorly in high density condition, as the number of nodes increases, the collision probability increases very rapidly [17].

Table I shows the comparison between Wi-SUN, LoRaWAN and NB-IoT in terms of its data rate, latency, communication range and current consumption. It shows that Wi-SUN has a higher data rate up to 300 Kbps and lower latency as compared to LoRaWAN and NB-IoT. Wi-SUN also seems to be the most power efficient protocol of the three. From a building management perspective, Wi-SUN appears to be the best suited long range communication protocol. While Wi-SUN provides a well-suited connectivity option for IoT devices,

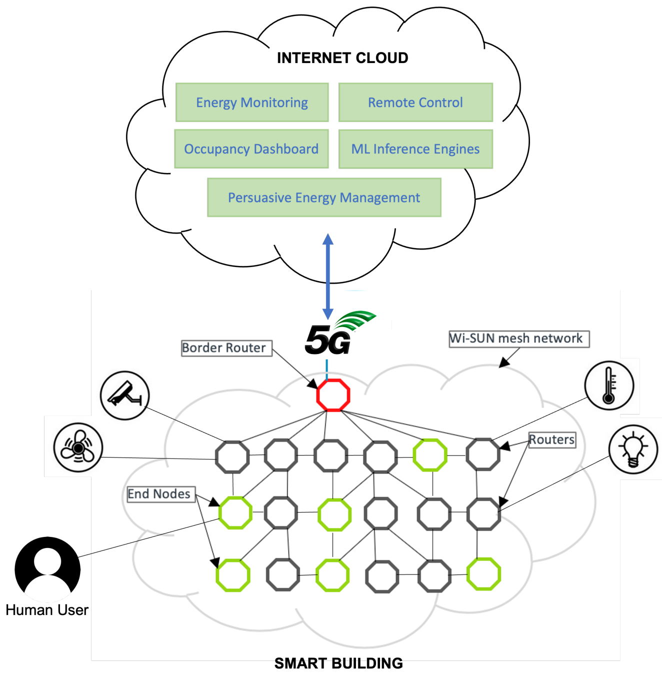

Fig. 1. The Architecture of 5G-Wi-SUN for Building Management System.

consumer-grade Wi-SUN devices are not readily available on the market, which presents a challenge in deploying a solution purely based on Wi-SUN. However, this presents an opportunity for combining Wi-SUN with more commonly used wireless protocols like Wi-Fi and Bluetooth, for instance, to communicate with personal devices [18]. Data is then relayed with the long-range, multi-hop features of Wi-SUN, and finally offloaded with Wi-Fi backhaul when the data is finally within Wi-Fi coverage. Such a hybrid system takes advantage of the commonality of Bluetooth in widely available smart devices, the long range of Wi-SUN, and the reliability and bandwidth of Wi-Fi with high signal strength.

III. Inter-networking 5G with Wi-SUN

This section first presents the envisioned 5G-Wi-SUN network architecture for optimising BMS and then followed by our prototype implementation.

A. 5G-Wi-SUN Network Architecture

Fig.1 shows the architectural overview of the envisioned 5G-Wi-SUN platform to enable the smart building management. The building is equipped with a Wi-SUN network [19], with the border router connected to the Internet cloud via 5G. The Wi-SUN network is mainly used for collecting and aggregating sensor data in the building, the aggregated data is then be sent to the cloud for analytics.

Wi-SUN provides a cost efficient way of extending connectivity. When compared with other common low-power personal-area network (PAN) communication protocols like Bluetooth and Zigbee, Wi-SUN was developed to reach hundreds of metres of range, which could be further extended by using Wi-SUN routers with its mesh multi-hop feature, albeit at a cost of latency. The mesh multi-hop feature enables the Wi-SUN network to scale, bound only by latency requirements. While IoT devices indoors would not be physically too far apart from each other, various building features like walls can severely impact wireless communications. The sub-GHz property of Wi-SUN means that it is less susceptible to interference from physical objects, and will avoid congestion in the overcrowded 2.4 GHz frequency band, which is popular with many different protocols. This makes Wi-SUN suitable for both outdoor and indoor environments.

When comparing with some other low-power wide-area networks (LPWAN), the open-standard nature of Wi-SUN, backed by rigorous test programs and certifications like the Wi-SUN FAN profile [20] enables cross-vendor interoperability, thus giving Wi-SUN an edge in adoption. The mesh multi-hop feature of Wi-SUN also gives it an advantage in reliability, as compared to star topology networks used by other LPWAN. A mesh topology usually performs worse than a star topology. However, Wi-SUN is capable of achieving higher bandwidth and lower latency when compared to star topology networks like LoRaWAN and NB-IoT [4]. This is further enhanced in the new Wi-SUN FAN 1.1 profile, with the introduction of orthogonal frequency-division multiplexing (OFDM) [21] [22], allowing for bandwidth up to 2.4 Mbps. Higher data rates also mean that Wi-SUN devices can spend less time transmitting, which reduces its energy consumption and allows devices to last longer out in the field. With 5G as WAN backhaul, a hybrid network of 5G and Wi-SUN can be designed and deployed anywhere swiftly while requiring no prior infrastructure setup. Thus, connectivity can be easily extended even into 5G dead zones.

B. Prototype Implementation

In Singapore, the regulatory body has allocated the frequency bands of 866 MHz and 920 MHz for LPWAN use, but has also indicated intentions to repurpose the 866 MHz frequency band [12]. Our prototype was implemented using the EFR32FG25 development boards from Silicon Labs [23] which supports the Wi-SUN FAN 1.1 profile though it has yet to be developed for Singapore's regulatory domain. As a result, our network was configured according to Japan's regulatory domain which had also allocated 920 MHz for LPWAN uses. With the FAN 1.1 profile, our Wi-SUN network was configured with OFDM, alongside a 800 kHz frequency bandwidth, thus giving data rates of up to 1.6 Mbps. A EFR32FG25 development board was connected to a Raspberry Pi 4, functioning as a Wi-SUN Border Router and gateway. A Zyxel NR5103 5G NR Indoor Router was used as the 5G CPE, this makes a customised Wi-SUN Border Router/gateway with 5G connectivity as shown in Fig.2.

In terms of the software communication stack, Silicon Labs (Silabs) has provided support for the widely familiar Portable Operating System Interface (POSIX) sockets, which the border router/gateway uses to interact with other Wi-SUN nodes using IPv6, through a TUN network interface configured for the

Fig. 2. A Customised Wi-SUN Border Router with 5G Connectivity

Wi-SUN Border Router application. POSIX sockets were also used to communicate to the Internet cloud through an Ethernet interface connected to the 5G CPE. Fig. 3 illustrates the network architecture of 5G-Wi-SUN network in our prototype implementation. The Wi-SUN nodes and the Wi-SUN Border Router/gateway were connected within an IPv6 subnet using Wi-SUN, while the gateway was connected to the 5G CPE in an IPv4 subnet. The gateway forwards data received from the Wi-SUN nodes to the Internet and vice versa. Additionally, for benchmarking purposes, the gateway was connected to a fibre broadband network via Ethernet to the Internet.

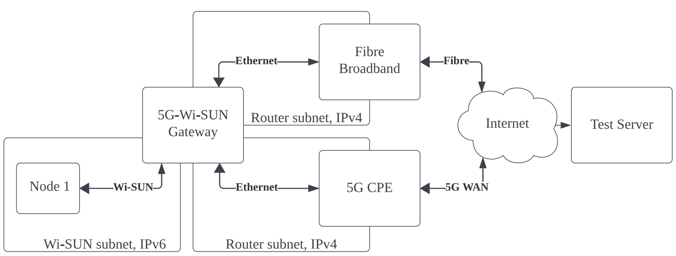

Fig. 3. Network Diagram of Wi-SUN Network with 5G Connectivity.

The multi-hop mesh feature of Wi-SUN was also evaluated in the proposed the 5G-Wi-SUN network. The Wi-SUN network was configured such that each Wi-SUN node maintains a whitelist of its adjacent nodes, so that it can only connect to the network via its neighbour node. The multi-hop experiment was set up by forcing the Wi-SUN network to adopt a line topology as shown in Fig.4 and subsequently measuring the multi-hop meshing capability of Wi-SUN used together with 5G.

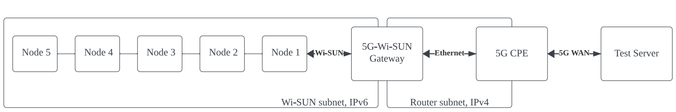

Fig. 4. Network Topology of the Wi-SUN multi-hop setup.

IV. Preliminary Results

Based on the network setup as shown in Fig.3, we evaluated the performance of 5G-Wi-SUN network in comparison with Fibre-Wi-SUN setup in an indoor environment. A Wi-SUN node was placed approximately 3.2m away from the Wi-SUN border router/gateway, and separated by a 32cm thick concrete wall in between. We sampled 3000 packets sent in one second intervals, each containing 64 bytes of data. Here, a small data size was used to emulate the conditions of a typical sensor-based application, which would usually transmit small data packets containing its measurement values periodically. We compared the latency of the following configuration:

- *Standalone 5G* - Wi-SUN border router/gateway connects to the test server via the 5G CPE, the test server echos the data via TCP.
- *5G and WiSUN* - test server initiates a TCP connection to send data packets to the Wi-SUN border router/gateway via the 5G CPE, which is then forwarded to the Wi-SUN node.
- *Fibre Broadband and WiSUN* - similar to *5G and WiSUN*, instead of using 5G CPE, the test server sends data packets to the Wi-SUN node via fibre broadband.
- *Standalone Wi-SUN* - data packet is sent between the Wi-SUN node and Wi-SUN border router.

The round-trip time (RTT) of the data packet was recorded by measuring the time taken to send and receive the data packet at the different components in the network setup. As there is no static IP address service offered for 5G mobile broadband service providers, this means that the network will be deployed behind carrier-grade network address translation (CGNAT). Often combined with a firewall, a CGNAT makes it challenging to implement User Datagram Protocol (UDP) type sockets with 5G. While UDP hole punching techniques exists, it does not guarantee success. For performance evaluation purposes, we used TCP connection to measure the RTT in order to maintain fair test conditions.

TABLE II
Comparison of RTT between different Network Configurations.

	5G	*Wi-SUN (TCP)*	*5G + Wi-SUN*	*Fibre + Wi-SUN*	*Wi-SUN (UDP)*
Trimean	24ms	85ms	115ms	88ms	71ms
99^{th} Percentile	39ms	367ms	404ms	374ms	339ms
Standard Deviation	6ms	71ms	86ms	78ms	66ms

*Note: Values are rounded off to the nearest ms

As shown in Table II, we compared the results of each network configuration using the trimean, the 99^{th} percentile, and standard deviation (SD) of the RTT measured for the data packets. Trimean is a measure of central tendency, giving extra weight to the median which results in lower sensitivity to outliers. This makes trimean more suitable for datasets that do not follow a Gaussian distribution.

To support low-power devices, Wi-SUN trades data rate and latency for power efficiency which results in a significantly higher RTT as compared to 5G. However, this RTT is still

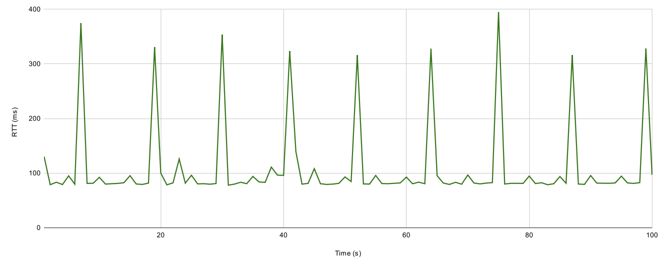

Fig. 5. RTT of Wi-SUN over time.

low enough for many sensor-based control applications used, for instance, in BMS and related domains. If we consider the latency of Wi-SUN as half of RTT, i.e., 42.5ms, it will usually still be acceptable for non-critical applications, such as automatic door control or smart lighting. Another critical aspect of a Wi-SUN-based network can be its low stablity as it tends to have a much higher SD as compared to the 5G only network. In Fig. 5, we observed that the RTT of Wi-SUN generates periodic spikes, and this are likely results from signaling events in the Wi-SUN network, which negatively impacts its performance [24]. Network management events such as PAN advertisements and channel hopping will take precedence over data transmission, and this causes unavoidable periods of less stable performance. PAN advertisements and broadcasts are needed to allow new or disconnected devices to join the Wi-SUN network, while channel hopping greatly improves reliability in wireless networks, which ultimately leads to increased throughput. The 99^{th} percentile RTT values of the Wi-SUN-based networks are less than half a second indicating response times that are less than 500 milliseconds in most cases. This means that even time-series data can be supported, as long as time resolution requirements are above those values. In essence, if low latency and tight stability are not strict requirements, then Wi-SUN can be an appropriate choice to reduce power consumption and increase the longevity of devices.

While not a match for fibre broadband, 5G still has a fairly competitive performance. When fibre broadband is used instead of 5G for WAN backhaul in the Wi-SUN hybrid network, faster RTT and lower SD were observed. This indicates a higher latency and lower stability when using 5G over fibre broadband. However, public 5G does not require cabling, and can be deployed anywhere within the telecommunications company's 5G service area. Hence, The latency and stability trade-off could be well worth the convenience brought about by 5G.

While most of the evaluation conducted in this study used TCP, we have also included results for a UDP Wi-SUN network in Table II. While congestion control in TCP allows it to more efficiently make full use of data bandwidths and achieve higher constant throughput, this is only applicable when transmitting large amounts of data. In our scenario, the periodical small data packet transmissions favour UDP much more as it has less overhead. This results in a lower RTT as compared to TCP, indicating better performance. With sensor-based applications that send only small amounts of data, UDP could be a better choice of transport protocol. In contrast, the extra overhead of TCP leads to more time spent on transmitting, and inevitably higher power consumption. This is not desirable for energy-constrained devices. In our UDP test, the packet delivery rate (PDR) was actually at 100% and while packet delivery is not guaranteed with UDP, the PDR of Wi-SUN with UDP in indoor environments are likely to be acceptable.

TABLE III
RTT of 5G with Wi-SUN Multi-hop Mesh Network.

	Node 1	***Node 2***	***Node 3***	***Node 4***	***Node 5***
Trimean	177ms	314ms	270ms	321ms	378ms
99^{th} Percentile	568ms	689ms	722ms	637ms	778ms

Values are rounded off to the nearest ms

Lastly, the 5G-Wi-SUN multi-hop mesh evaluation was conducted with all the Wi-SUN nodes within the same room in close proximity. Table III shows the RTT performance of Wi-SUN multi-hop, for up to five hops for Node 5. It is observed that even in a scenario requiring five hops over four intermediary nodes, the 5G-Wi-SUN network keeps the latency to less than half a second. While this is well within Wi-SUN FAN specifications, the hops over intermediary nodes could introduce too much lag for use in actuators. However, with a latency specification of up to one second, the Wi-SUN multi-hop is still capable enough for frequent data transmissions.

V. Conclusion and Future Work

A hybrid network using 5G and Wi-SUN is presented to demonstrate the ability and benefits of 5G networks to be extended with a purpose-built LPWAN like Wi-SUN. While 5G can provide convenient WAN access, the network will be better suited in a BMS when augmented with Wi-SUN. We analysed and compared the performance of a 5G network, a Wi-SUN network, a 5G-Wi-SUN network and a fibre broadband-Wi-SUN network. Our test results show that Wi-SUN can provide a highly suitable connectivity solution for an IoT network. When used in combination with 5G, it offers an excellent network capable of being set up anywhere within 5G service areas.

While the performance of Wi-SUN over a single hop and multi-hop was evaluated, further work is required to study the impact of implementing a Wi-SUN network in a larger and more complex environment where data transmission would be affected by several factors such as distance and building structure, resulting in performance degradation which could be mitigated with efficient placement of additional 5G gateways. Moreover, as our test results indicated that UDP could be better suited for Wi-SUN, the future work will study 5G-Wi-SUN networks using both TCP and UDP in specific practical applications involving sensors and actuators.

Acknowledgment

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