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# NB-IoT and Wi-Fi Technologies: An Integrated Approach to Enhance Portability of Smart Sensors

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**ABSTRACT** The Internet of Things paradigm has expanded the possibility of using sensors ubiquitously, particularly if connected to a cloud service for data sharing. There are several ways to connect sensors to the cloud: wearable or portable devices often lean on a smartphone that acts as a gateway, while other sensors, such as smart sensors for continuous monitoring (e.g. fall detectors) are connected through wireless networks covering a limited area (e.g. ZigBee or Wi-Fi). Their functionality can be improved using them in both outdoor and indoor environments without other devices. NB-IoT is a recently introduced wide-range protocol with a good compromise between low power, low deployment costs, payload length, and data rate. Traditionally, sensor nodes rely on only one type of radio: an innovative solution could be a sensor node exploiting a combination of different transmission technologies with the aim of achieving higher portability. In this paper, a hybrid solution based on NB-IoT/Wi-Fi is presented. The Wi-Fi connection is primarily selected due to its lower power consumption (compared to NB-IoT), while NB-IoT is activated only when a Wi-Fi network is not available. This study aims to evaluate the power consumption of the proposed solution with respect to single radio NB-IoT technology. Test boards have been implemented, and several data transmission tests have been carried out with both NB-IoT and Wi-Fi radios. Different received powers and payload lengths have been considered to analyze the impact on the energy profile of smart sensors. It has been demonstrated that using NB-IoT for both indoor and outdoor leads to an acceptable battery discharge time, with a strong dependence on the payload length. Under certain conditions, the proposed hybrid solution results in a battery duration up to two times higher than single-radio NB-IoT.

**INDEX TERMS** Sensor systems and applications, smart devices, power measurements, low-power electronics, Internet of Things (IoT).

## I. INTRODUCTION

Internet of Things (IoT) is a neologism that expands the Internet concept to the world of objects. It describes a system designed to connect many heterogeneous devices such as sensors, cameras, home appliances, medical devices, and others to the Internet [1]. The goal is to infer more information than the single device could provide, enhancing the efficiency in solving problems in various applications such as home automation [2], ambient assisted living [3], manufacturing [4], etc. Recently, IoT has been expanded to the framework of systems designed to foster people's health [5]–[7], monitoring user daily activity [8], [9], facilitating early diagnosis [10], [11], and increasing the value of life. In this context, smart wireless sensors occupy a key role since they can be adapted to different locations and can be used to profile users. Connecting them to a cloud service is a common feature that allows data sharing with caregivers and/or physicians. Wearable sensors monitoring the user's daily activity or portable diagnostic devices [7], [10], [12], [13] have been traditionally conceived for indoor use. In this field, several wireless technologies can be deployed to transfer data over the Internet, with different features regarding, for example, network coverage, ease of use, and power consumption [14]. ZigBee and Wi-Fi are the preferred solutions [12], [14] both in Point-of-Care (PoC) or home context. ZigBee exhibits a lower power consumption, but it requires a dedicated network [15]. Instead, Wi-Fi is widely used in home and office contexts for its easier setup and higher data rate. Furthermore, devoted energy management solutions have been proposed to obtain a power consumption of Wi-Fi devices compatible with the requirements of Wireless Sensors (WSs) [15], [16].

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The possibility to extend the use of smart sensors outdoors could enable additional features. For example, a wearable sensor device dedicated to activity recognition [8] would allow complete monitoring if available 24-hour a day. A wireless sensor for medical or healthcare applications could operate in different locations, such as PoCs, not necessarily covered by a local wireless network. Smart wireless sensors frequently rely on other devices (e.g., smartphones) to enable these features. The development of a stand-alone solution would improve both the portability and ease of use, limiting at the same time the system costs. To this aim, the front-end radio of the WS could be designed to deploy one of the traditional wireless technologies for mobile phones, from 2G to 4G standards[16]. Still, the power consumption would be excessive for the considered application domain.

Recently, several low-power wireless communication protocols featuring wide coverage and, thus, suitable to extend the operation of the sensor to the outdoor environment have been introduced. The most promising solutions are LoRaWAN, Sigfox, and the Narrow Band technology for the Internet of Things (NB-IoT) [17]–[19]. LoRaWAN is a very attractive solution allowing up to 300 bps data rate, but it requires the deployment of a specific network infrastructure [20]. To achieve the successfully received message ratio, it exploits redundant reception, involving high deployment costs [17]. SigFox networks are based on proprietary base stations, and they are already present in 31 countries. However, the number of daily uploaded messages is limited to 140, with a maximum payload of 12 bytes per message [19]. Also, the downlink is limited to 4 messages per day with 8 bytes payload [17]. These constraints prevent the SigFox adoption in some applications that require continuous monitoring. Indeed, a typical example, where the allowed data size is easily saturated, is the three-axis accelerometer and gyroscope sending one data word per minute. Moreover, the downlink limitation is critical in those applications requiring access to data that have been previously stored in a cloud space (e.g., calibration data of portable sensors for disease diagnostic [21]).

NB-IoT has recently been made available by several mobile network providers [22]. This technology, designed for low data rates, allows achieving a very low power consumption. Moreover, a NB-IoT device has the advantage of leveraging LTE infrastructure, thus reducing deployment burden and costs. Eventually, it exhibits a higher payload length and better scalability than LoRaWAN and SigFox, ensuring a guaranteed Quality of Service (QoS) [17].

The cited technologies are generally exploited as standalone solutions [23]–[25]. Recently, some hybrid solutions have been presented in the literature. In [26], a multiple communication interface node, compatible with several IoT protocols, such as Wi-Fi, LoRaWAN, and NB-IoT, is presented. However, the sensor nodes can be equipped with only one radio device, thus preventing real-time switching between different wireless networks. A system combining LoRaWAN with NB-IoT is presented in [27]. However, the sensor node exploits only the LoRaWAN protocol, and an external gateway device is mandatory for compatibility with the NB-IoT network. A similar solution with LoRaWAN and Wi-Fi is reported in [28]. Here, depending on the transmission range, each sensor node exploits only one technology, relying on an external gateway to share data among all network nodes.

An innovative solution consists of a hybrid architecture combining, at the sensor level, a local-area link for indoor environments (either Wi-Fi or ZigBee) with a wide-coverage technology for outdoor use. The system should prioritize the protocol that exhibits the lower energy consumption, automatically switching to the other one when the correspondent wireless connection is not available.

In this paper, a sensor node combining Wi-Fi for local area networks and NB-IoT for maximizing portability has been investigated. This solution features the low deployment costs of these two technologies and the scalability and larger payload length of the NB-IoT with respect to LoRaWAN and SigFox. In this scenario, the sensor node is usually connected to a Wi-Fi Access Point (AP), switching to the NB-IoT service only when it is moved to an area with no available Wi-Fi network. Thus, the portability of the WS is maximized through the NB-IoT link, while the lower energy consumption is achieved with the Wi-Fi radio device.

It is worth noticing that this WS does not need any external device such as a dedicated gateway or a mobile phone, thus dramatically reducing the system's complexity. To the authors' knowledge, such a hybrid architecture has never been considered in the literature, nor has its energy consumption been evaluated.

This proposed hybrid solution has been compared to the case of WSs with a single radio (i.e. NB-IoT) used for both indoor and outdoor operations. NB-IoT performance has already been analyzed in the literature in different conditions (i.e. distance to the base station) [29]. Further measurements are presented in this paper to compare the energy performance of the single radio vs. the combined NB-IoT and Wi-Fi radio for a WS application.

In particular, it is found that the proposed architecture outperforms the NB-IoT single radio in typical operating conditions, which are discussed in the reported analysis. Moreover, a cost comparison, considering the latest devices available on the market, is presented.

In summary, the analysis and the results reported in the paper are extremely useful to optimize the design of the radio front-end and back-end of a low-power WS conceived for indoor and outdoor usage.

The paper is organized as follows: in section II the measurement set-up is described, in section III the measurements performed are reported, whereas results are discussed in section IV. In section V conclusions are drawn.

## II. SYSTEM SET-UP

Two test boards have been implemented to measure the energy consumption corresponding to the transmission of a data word, with either a Wi-Fi or an NB-IoT chipset.

The TI CC3200 System-on-a-Chip (SoC) was used as Wi-Fi radio [30], whereas the NB-IoT test-board was equipped with a U-blox SARA-N210 [31] connected to a Vodafone SIM. A Renesas Micro-Controller Unit (MCU) was used to transfer data and AT commands from a laptop (through a USB port) to the UART port of the SARA chip. Since only the UDP socket is supported by the NB-IoT device, this protocol was used for all the measurements with both devices. It is worth noticing that other Wi-Fi SoCs and NB-IoT devices, i.e. [32], [33], are available on the market, with performance and consumption similar to those of the aforementioned devices selected for the analysis.

The supply current waveform of each radio device was captured with the current-sense circuit in Fig. 1. The voltage across the sensing resistor $R_{SH}$ is amplified by a high-side current-sense amplifier [34], with the voltage gain set by resistive feedback, i.e., $R_{G1}$ and $R_{G2}$.

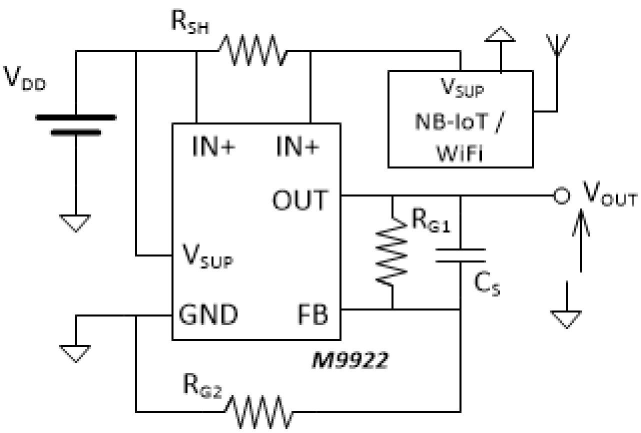



**FIGURE 1. Circuit for supply current measurement of Wi-Fi and NB-IoT devices.**

The maximum value of the series resistor $R_{SH}$ depends on the peak value of the supply current and is set by the maximum voltage drop tolerated by each radio device. From the specifications of the Wi-Fi and NB-IoT devices, the upper limit of the voltage across $R_{SH}$ was set to 150 mV, leading to a 0.1% maximum linearity error affecting the I/O amplifier characteristic.

The minimum value of the sensing resistor is defined by the amplifier offset error, the input noise, and the maximum voltage gain. Indeed, considering an open-loop bandwidth of about 1 MHz for the amplifier, the voltage gain should not exceed the value of 23.5 dB if a minimum 50 kHz bandwidth is required for an acceptable output settling error. Considering that both the offset voltage and the input-referred noise voltage are as low as few tens of microvolts, the lower limit of the voltage across the sensing resistor is set by the constrained maximum gain.

The NB-IoT device exhibits four operating modes: Power Save Mode (PSM), idle, receiver, and transmission mode. The lowest power consumption occurs in PSM with a typical supply current of 3 $\mu$A. In RX or TX mode (with 23 dBm output power), the average consumption rises to 46 mA or 220 mA, respectively [25]. It is worth noticing that the specified current consumptions are averaged over either a 2 s or 10 s time interval for the RX or the TX mode, respectively.

The Wi-Fi radio exhibits a similar supply current range with 4 $\mu$A in power saving mode and up to 278 mA and 59 mA of current consumption in TX and RX modes. Therefore, with a 0.6 Ω shunt resistor, a voltage drop lower than 150 mV is obtained considering the average supply current, thus compatible with the linear range limit of the current sensing amplifier. Moreover, with a voltage gain of 22.3 dB, the output voltage ranges approximately from 350 mV to 1.7 V for the NB-IoT RX and TX mode, respectively. Such range is suitable for capturing the supply current waveform with a Keysight InfiniiVision MSO-X 2024A oscilloscope. Only for the measurement of the supply current in PSM for the NB-IoT and the Wi-Fi devices, both the gain and the sensing resistor are increased to obtain a correspondent output voltage in the hundreds-millivolt range.

The measured V/I characteristic of the current-sense amplifier is shown in Fig. 2. A significant deviation from the linear behavior occurs at approximately 270 mA since the input voltage approaches the upper limit of the linear range of the differential amplifier. This leads to an overestimation of the supply current from the measured $V_{OUT}$ if a linear fitting is used up to the peak current in the TX mode. Indeed, the supply current values, reported in the datasheet for the NB-IoT device, are averaged values over 10 s. Therefore, the peak supply current in TX mode is expected to exceed the linear range of the I/O characteristic in Fig. 2. To overcome this problem, the experimental data are fitted with a first-order polynomial up to 270 mA and with a two-term power function at higher values of input current:

$$V_{OUT} = a \cdot (I_{DD})^b \, \forall I_{DD} \geq 270 \, mA \tag{1}$$

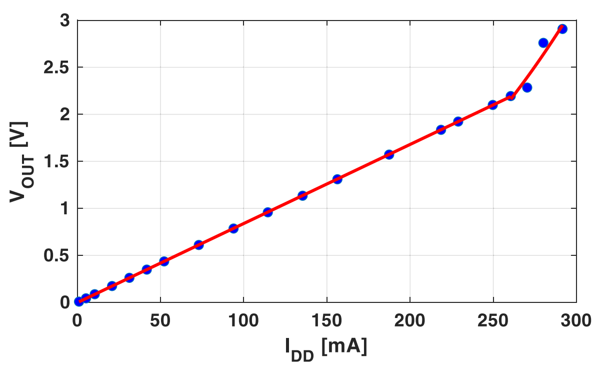



**FIGURE 2. Measured I-V characteristic, circles, with fitting, solid line.**

The resulting fitting function corresponds to the solid line in Fig. 2.

Concerning the antennas used in the experimental setup, a TAOGLAS low-profile antenna with an average gain of −2.5 dB was connected to the NB-IoT board through a power attenuator (50DR-001 of JFW Ind.). The attenuation emulates the effect of moving the device further away from the first available Base Station (BS), which provides the NB-IoT service. For the Wi-Fi chipset, a chip antenna was used.

The test-bench setup is completely automated with a MATLAB script running on a laptop connected to both the microcontroller in the test board and the oscilloscope through USB ports.

## III. MEASUREMENTS

The transmission measurements were carried out with a payload size from 4 to 500 bytes for both Wi-Fi and NB-IoT transceivers. Data words of 4 and 16 bytes are suitable for WSs aimed at disease diagnostic [21]. In Fig. 3, a Wi-Fi current waveform example is reported. The first phase (I) corresponds to the system power-up and setup. In the second segment (II), the device is connecting to the AP. In the last phase (III), data are transmitted, and the connection is closed.

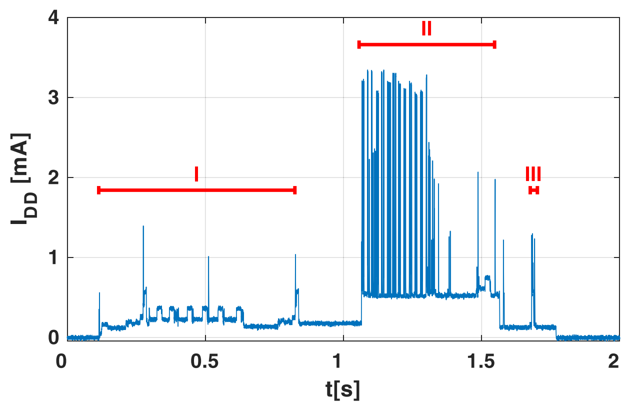



**FIGURE 3.** Wi-Fi supply current waveforms (I system set-up, II connection to the AP, III data transmission and closing connection).

Wi-Fi measurements were acquired on two different days, and include both the connection to the AP and the data transmission. When the device reboots after a PSM period, it should reconnect to the AP. This contribution is considered for every data transmission, which is the worst condition for energy consumption.

Measurements with NB-IoT radio were repeated for each payload on different days and in two places. Four attenuation levels were used to change the received signal power from −75 dBm (no attenuation) to −122 dBm. A total of about 2650 data has been acquired. The cellular tower providing the NB-IoT service is located 400 m from the measurement setup. According to Friis' law, the maximum attenuation corresponds to a distance of about 15 km with a path loss exponent equal to 3, which is a typical value in the case of an urban environment. The value of the received input power was measured by the NB-IoT device [22].

Once the User Equipment (UE) corresponding to the NB-IoT radio has completed the network registration, it remains in the PSM until a data message is queued for upload. Before each transmission, the UE performs a Random Access Channel Procedure (RACH) to establish a Radio Resource Control link (RRC) to the BS. The data word is split into Transport Blocks with lengths from 2 to 125 bytes in the upload. In this phase, the UE is under the control of the BS, which sets the coverage Enhancement Level/Class (ECL) from 0 to 2 and the data repetitions, based on the input Signal-to-Noise Ratio (SNR). Thus, operating in deep indoor environments or at large distances from the BS forces the UE in ECL 1 (or even ECL 2), leading to higher energy consumption due to more repetitions occurring in the data upload.

When the data transmission is completed, the NB-IoT radio switches to the RX mode, waiting for an incoming message from the network. The length of this phase, usually a few seconds, is set by a specific network-dependent timer. Since the current consumption of the NB-IoT device in the RX mode is approximately 50 mA, this configuration causes a significant waste of battery power if the UE is primarily used to upload data to the network. The problem can be managed by exploiting the release assistance feature to release the RRC and to immediately switch the device to idle mode when the transmission is completed. In the idle mode, the UE can still activate the radio receiver for a short time interval to download any incoming message from the network (e.g., an acknowledge message) if the Discontinuous Reception (DRX) is enabled [35]. This feature, scheduled by specific timers, may be disabled with a further power saving if the WS should only upload data and no acknowledge message is expected to be downloaded. In any case, when the T3324 timer expires, starting from the completion of the transmission phase, the device enters in PSM with a current consumption of a few microamperes [22].

The supply current ($I_{DD}$) waveforms for a single data-send command are shown in Fig. 5(a) and (b) for ECL 0 and ECL 1 coverage, respectively. The first phase (I) corresponds to the RACH procedure to establish the RRC connection with the BS. In the next phase (II), the data word is transmitted to the network. It is worth noticing that due to a higher repetition frequency forced by the BS to compensate for the lower SNR, data transmission requires a longer time in ECL 1 than in ECL 0, the same word length being considered. Since the Release Assistance has been used, once the word transmission has completed, the device is immediately switched to the idle mode (phase III).

In this phase, the device considered for the experiment exhibits a measured current consumption of about 7 mA. When the specific timer expires, the device is set in PSM with a current consumption of a few microamperes. The last phase is not shown in Fig. 5(a) and (b). Before the expiration of the related timer, the device is set in DRX mode for about 1 s to download any incoming or acknowledge message from the network (phase IV).

The $I_{DD}$ waveforms for the network registration phase are shown in Fig. 4(a) and (b) for the ECL 0 and ECL 1 coverage, respectively. It is worth noticing that once the network registration has been completed, the UE can stay in the

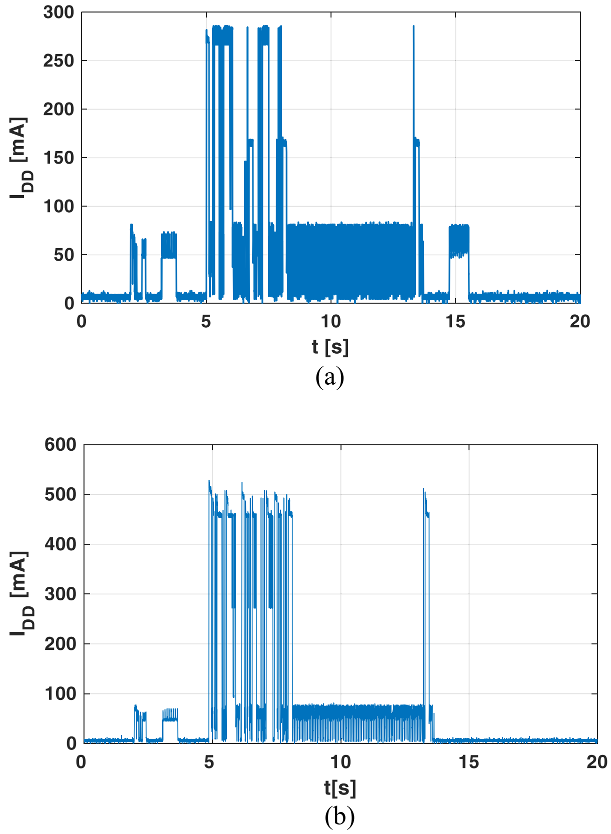



**FIGURE 4.** **NB-IoT supply current waveforms during network registration: (a) with ECL 0 coverage, and (b) with ECL 1.**

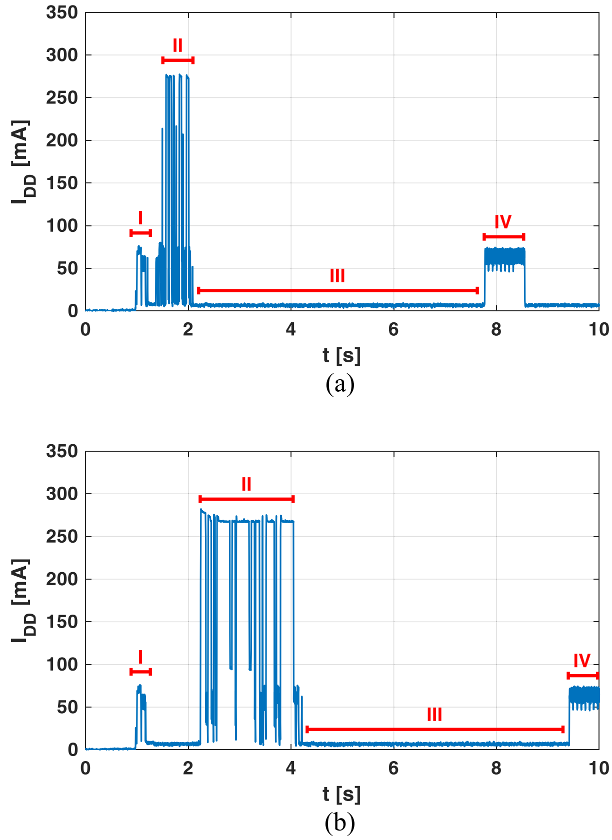



**FIGURE 5.** **NB-IoT supply current waveforms: (a) data send (NSOSTF command) with ECL 0 coverage, and (b) with ECL 1 (I open, II transmission, III idle mode, and IV receiver enabled).**

PSM for several days without repeating the registration process, which is quite expensive in terms of battery energy. The maximum time interval in PSM is set by the Tracking Area Update (TAU) timer, which is assigned by the network and usually corresponds to several days [35].

From the measured waveforms of Fig. 4(a) and (b), the daily average current consumption is 15 $\mu$A with ECL 0 coverage and 24 $\mu$A with ECL 1. Since the UE can stay in the PSM for several days (depending on the TAU timer value), the daily average is used to estimate the overall energy consumption of one-day device usage.

## IV. RESULTS AND DISCUSSION

A first energy consumption evaluation of the two single-radio systems (either Wi-Fi or NB-IoT) has been carried out. Then, the hybrid solution capable of exploiting both technologies, selecting one of them depending on the operating conditions, has been introduced. In Fig. 6, a sketch of the three architectures is shown.

In the case of the WS with only the NB-IoT radio as in Fig. 6(b), an MCU must be included as an additional component, if an NB-IoT radio device is used [31], [32], [36], [37]. Alternatively, a Silicon-in-Package device embedding both the NB-IoT and the MCU can be used, leading to a single-chip solution [33].

In the case of the hybrid solution in Fig. 6(c), the Wi-Fi link is the primary choice (for the lower energy consumption) to upload the sensor data to the cloud, whereas the NB-IoT link is exploited when no Wi-Fi hotspot is available, i.e. a typical situation in outdoor use. To minimize the component count, which is important for the system costs, we consider a hybrid solution based on only two devices: a SoC embedding the Wi-Fi radio with an MCU [30] and an NB-IoT device [31], [32]. Thus, the MCU in the SoC is used to control also the NB-IoT radio. Hence, it can be observed that, at the present day, the proposed hybrid solution requires a couple of radio chipsets with the related antennas. Thus, the single-radio device is expected to exhibit lower production costs and smaller size. However, even if the rapid evolution of the market does not allow for reliable long-term assessments, more detailed cost analysis has been carried out. The system in Fig. 6(a) exhibits the lower cost, which is currently in the range of 7$ to 10$, considering only the SoC device [35] in the figure with a Surface Mount Device (SMD) antenna.

Concerning the NB-IoT solution in Fig. 6(b), the cost is in the range of 9$ to 15$ for the NB-IoT radio device and within 5$ for a MCU featuring a standby current of tens of nanoampere [38], [39]. It is worth noticing that some NB-IoT devices have recently been made available on the market at about 5$. Silicon-in-Package solutions embedding

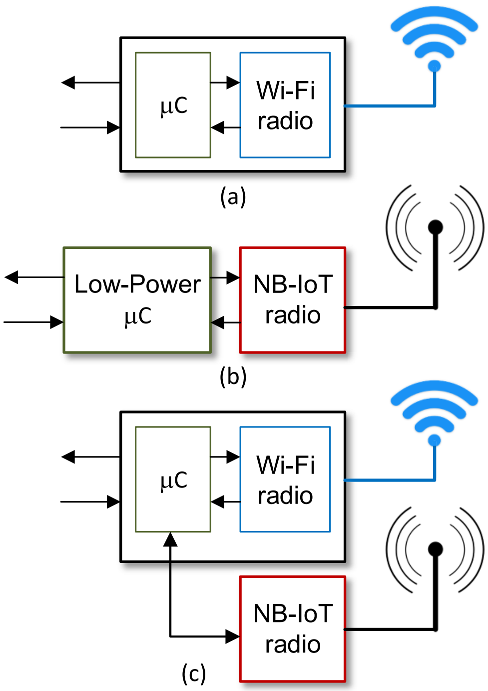



**FIGURE 6.** Radio architectures for a WS with minimum component count: (a) and (b) single-radio solutions with either Wi-Fi or NB-IoT radio; (c) hybrid solution combining Wi-Fi and NB-IoT.

both the MCU and the NB-IoT radio [33] can be found at a cost in the range of 12-20$.

Based on this analysis, we can conclude that removing the low-power MCU partially balances the Wi-Fi radio overhead in the system of Fig. 6 (c).

Furthermore, low-cost SoC devices embedding a low-power MCU and a Wi-Fi radio have been recently made available on the market at a price of few dollars [40]. Thus, the component cost of the hybrid solution should approach the price of a single radio NB-IoT solution.

In the following paragraphs, the two solutions have been compared in terms of power consumption.

### A. SINGLE-RADIO SOLUTIONS COMPARISON

At first, single-radio solutions are compared to evaluate the impact of replacing Wi-Fi technology with NB-IoT on the battery runtime of a smart sensor for personal monitoring.

To evaluate the battery life, $n$ events sensor activations per day are considered. The average daily current is calculated as:

$$I_{day} = \frac{1}{24}(n\,(I_{tx}t_{tx}) + I_{PSM}\,(24 - nt_{tx})) \tag{2}$$

where $I_{tx}$ and $I_{PSM}$ are the average current in the TX and sleep mode, respectively, and $t_{tx}$ the transmission time in hours. The data processing time is not considered since the related power consumption is negligible with the last generation low-power MCUs [15]. In the case of NB-IoT single radio solution, $I_{PSM}$ should also include the microcontroller sleep current. However, this contribution can be disregarded since low-power devices exhibit standby currents within a few hundreds of nanoamperes [38].

In Fig. 7, the mean and the standard deviation of the absorbed current by the radio device for 20 events/day are plotted vs. payload size for the Wi-Fi and NB-IoT case.

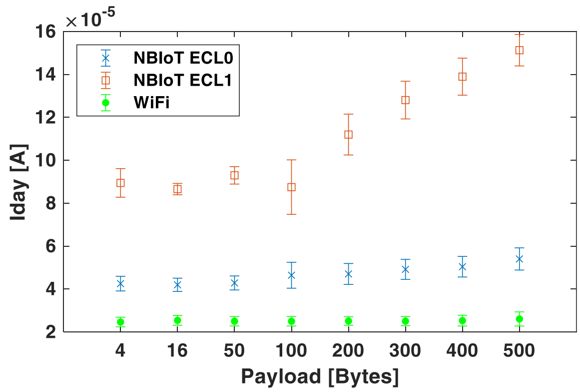



**FIGURE 7.** Average daily current measurements vs. payloads. For NB-IoT, squares and crosses refer to ECL 1 and 0, respectively.

In the case of NB-IoT, the transmissions were classified with the ECL level, irrespective of the signal strength. With the NB-IoT provider used for the experiment, no ECL 2 transmission was detected up to the maximum attenuation.

It is worth noticing that a NB-IoT radio operating in ECL 0 exhibits an average current consumption very close to the Wi-Fi. However, NB-IoT energy consumption is significantly affected by the payload. Thus, on-board data processing before transmission is of utmost importance in a WS with single radio NB-IoT.

Unlike the NB-IoT case, the Wi-Fi current consumption is almost constant with the payload length due to the higher contribution of the commissioning phase than the transmission one, as shown in Fig. 3. To better understand this point, the energy consumptions of the two phases are compared in Fig. 8. The energy has been evaluated considering the contribution of the average current in the commissioning or transmission phase and the time length of the phase considered, with a power supply voltage of 3.3 V. It is evident that the contribution of the commissioning phase is always higher at all payload lengths.

In Fig. 9, the battery life of Wi-Fi and NB-IoT devices is compared as a function of payload size. A 600 mAh battery capacity was considered with power levels of the NB-IoT signal ranging from −75 dBm to −122 dBm. The power level values have been grouped into four classes: class A from −75 dBm to - 85 dBm, class B from −95 dBm to −85 dBm, class C from −105 dBm to -95 dBm, and class D from −125 dBm to −105 dBm.

Collected data highlight how a weaker radio signal reduces the battery runtime due to the higher occurrence of uploads in the ECL 1 coverage class. The results in Fig. 9 show that NB-IoT WS exhibits a minimum 1 year battery life with a

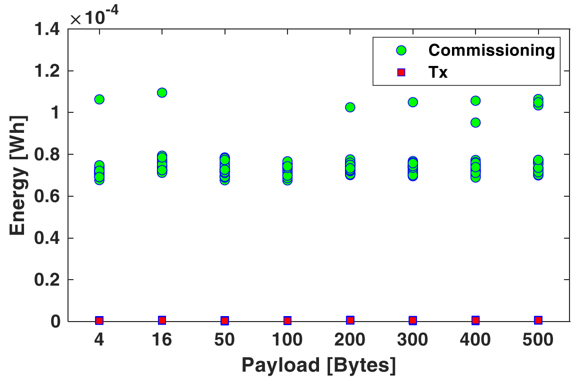



**FIGURE 8.** Comparison between Wi-Fi energy consumption in Commissioning phases and data transmission.

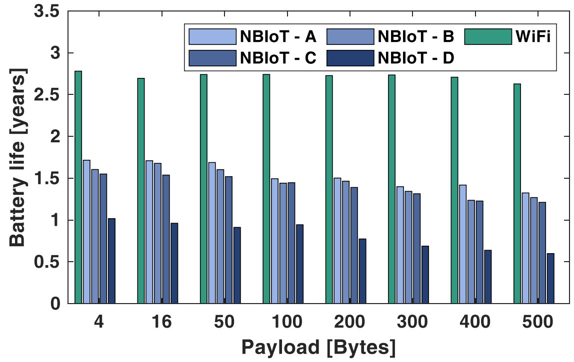



**FIGURE 9.** Battery lifetime with 20 events/day. Green bars refer to Wi-Fi. Increasing blue intensity corresponds to lower NB-IoT signal power: class A (−75 dBm:−85 dBm), class B (−95 dBm:−85 dBm), class C (−105 dBm:-95 dBm) and class D (-125 dBm: −105 dBm).

payload of up to 100 bytes, even when the UE is far from the cell tower and always operates in ECL 1 class.

Since a smart sensor must be able to connect to the Internet at any time and place, the single-radio Wi-Fi solution in Fig. 6(a) cannot be used, even though it is the most convenient in terms of both battery discharge time and component count. Replacing the Wi-Fi single-radio solution with a NB-IoT device enables both indoor and outdoor operations at the cost of increased energy consumption by a factor of two or even three. Nevertheless, a NB-IoT single radio solution exhibits a battery life that is still compatible with real use case scenarios. Increasing the number of events per day entails a decrease in battery life, with a similar impact on both Wi-Fi and NB-IoT solutions.

### *B. HYBRID SOLUTION EVALUATION*

Among the radio architectures in Fig. 6, only the NB-IoT radio in Fig. 6(b) and the hybrid solution in Fig. 6(c) support both indoor and outdoor use. We will demonstrate that a platform combining both the Wi-Fi and NB-IoT radios can be optimized for minimum energy consumption and outperforms the single radio architecture under specific usage conditions.

The evaluation of the battery life with a hybrid device is carried out considering the same 600 mAh battery as in the previous analysis. The average current over 24 hours, $I_{day}$, is computed considering the contributions of both the Wi-Fi and NB-IoT devices as:

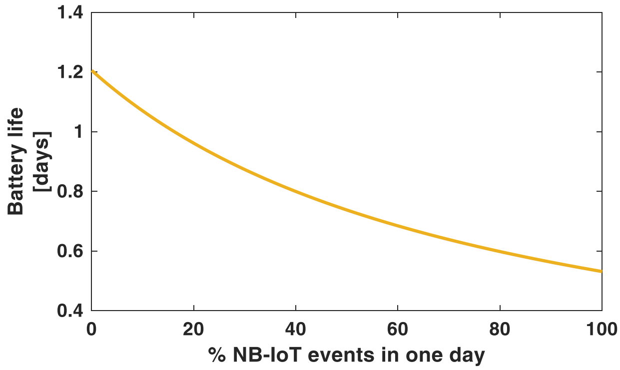
$$\begin{aligned} I_{day} &= 1/24[I_{comm\_N}t_{comm\_N} + n_w(I_{tx_w}t_{tx_w}) \\ &\quad + n_N(I_{tx\_N}t_{tx\_N} + I_{comm\_w}t_{comm\_w}) \\ &\quad + (I_{PSM_W} + I_{PSM\_N})(24 - n_W t_{tx\_w} - n_N t_{tx\_N} - t_{comm\_N})] \end{aligned} \tag{3}$$

where $n_w$, $I_{tx-w}$, $t_{tx-w}$, and $I_{PSM-w}$ refer to the case of the device exploiting the Wi-Fi connectivity and are, respectively, the number of data upload events, the average current and time in TX mode, and the average current in PSM mode. Furthermore, $n_N$, $I_{tx-N}$, $t_{tx-N}$, $I_{PSM-N}$ are the correspondent parameters for the data upload events performed with the NB-IoT link.

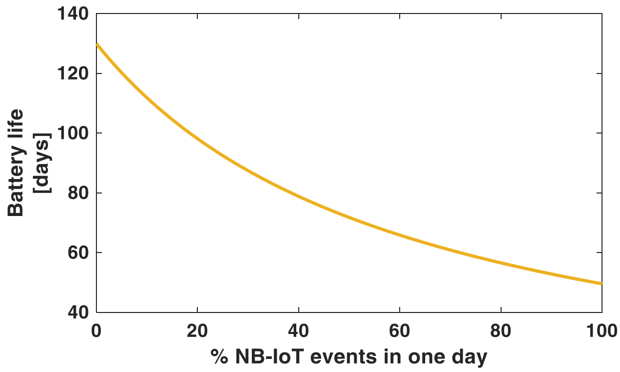
The hybrid solution exhibits a sleep current that is the sum of the PSM currents of the Wi-Fi and NB-IoT devices, respectively. $I_{comm-W}$ is the current consumption of the Wi-Fi device due to the search procedure for any available network. This contribution is considered for each data upload performed through the NB-IoT. In fact, with the hybrid solution, the Wi-Fi connection should be the first option for each transmission event since, as shown in Fig. 7, it requires lower energy consumption. When sensor data are ready to be uploaded, the hybrid system searches for any registered Wi-Fi hotspot. If the Wi-Fi search procedure fails, the Wi-Fi radio swaps to PSM mode, and the NB-IoT radio is resumed from the PSM to perform the pending communication. In the case of a Wi-Fi transmission, the commissioning contribution has already been considered in the $I_{tx-w}$ term. Similarly, $I_{comm-N}$ is the current consumption due to the NB-IoT network registration, which is assumed to occur once a day at the device reboot. It is worth noticing that the daily average value is used for all currents in (3). The number of daily data transmission events is estimated considering a typical WS with a data acquisition throughput of one byte-per-second. Data buffering capability is introduced in the WS to reduce transmission occurrences, either with the Wi-Fi or the NB-IoT link.

In Fig. 10(a) and (b), the battery runtime is shown as a function of the percentage of NB-IoT transmission events over the overall number of upload events occurring in a single day. Fig. 10(a) corresponds to the case of a small memory buffer register, i.e. 4 bytes, while in Fig. 10(b), a 500 bytes memory buffer is assumed. The former case leads to a data upload rate of one transmission every 4 seconds (corresponding to 21600 events per day). In the latter case, the data transmission occurs every 8 minutes, corresponding to 180 uploads per day.

The results in Fig. 10 show that regardless of the buffer memory size, the higher the number of data uploads with the NB-IoT radio, the shorter the battery life. Moreover, it can be observed that the battery life decreases almost proportionally




(a)




(b)

**FIGURE 10.** **Battery life vs. percentage of NB-IoT events, in the hybrid solution Wi-Fi + NBIoT: (a) 4 byte payload, 4s event time (b) 500 bytes payload, 8min event time.**

with the buffer size. For example, if all daily events are carried out through the NB-IoT link, with a buffer of 4 bytes (Fig. 10(a)), a battery duration of about 0.6 days is obtained, whereas 53 days are achieved with 500 bytes data buffering (Fig. 10(b)).

The hybrid architecture is then compared to a single radio system, where a NB-IoT device is combined with a low-power MCU, featuring a sub-microamperes standby current (Fig. 6(b)). The results of the comparison in terms of battery discharge time, considering a 600 mAh battery capacity, are shown in Fig. 12. A payload of 500 bytes is assumed with a time interval between successive transmission events of 8 min, 15 min, and 1 hour, corresponding to 180, 96, and 24 daily upload events. The correspondent results are shown in Fig. 12(a), (b), and (c), respectively, where the solid line refers to the hybrid radio solution (eq. (3)) and the dashed line to the NB-IoT single radio case (eq. (2)).

It is worth noticing that with 100% data upload with NB-IoT link, the hybrid solution exhibits lower battery life than a NB-IoT single radio. Indeed, the Wi-Fi energy consumption required to search for an available hotspot before each upload event, and the PSM current must be considered, as in eq. (3). Due to these contributions, the energy consumption of the hybrid architecture is higher with respect to the NB-IoT single radio. This is due to the solution adopted in the design phase: the hybrid sensor node exploits Wi-Fi primarily, since, as it can be derived from Fig. 3, it features a lower power consumption.

The intersection of the two curves in each plot defines the upper bound of the percentage of NB-IoT events to achieve a lower battery consumption with the hybrid radio. From this breakpoint to the fully outdoor operation (i.e., 100% NB-IoT usage), the NB-IoT single radio is the most efficient solution to be preferred in this operating range.

Interestingly, this hybrid-to-NB-IoT breakpoint moves to the left side of the graph (i.e. toward a lower occurrence of NB-IoT uploads) if the overall number of daily upload events is decreased or the memory buffer is increased (i.e. from Fig. 12(a), to Fig. 12(c)). Hence, if the WS is conceived for applications that require few uploads a day or for usage in environments with limited Wi-Fi availability, system designers should prefer the single NB-IoT radio because of the longer battery runtime. On the contrary, when more Wi-Fi events are expected (i.e. up to 50% of daily events), the hybrid solution outperforms the single radio NB-IoT in terms of power consumption leading up to double the battery life.

In Fig. 11, the number of NB-IoT transmissions (in percentage over the overall daily upload events) at the hybrid-to-NB-IoT breakpoint is shown as a function of the number of total events scheduled per day. Even if a large range of payload lengths is considered, it was found that the minimum number (in percentage) of daily transmissions, which makes the NB-IoT single radio a more convenient solution, always decreases with the number of daily transmission events.

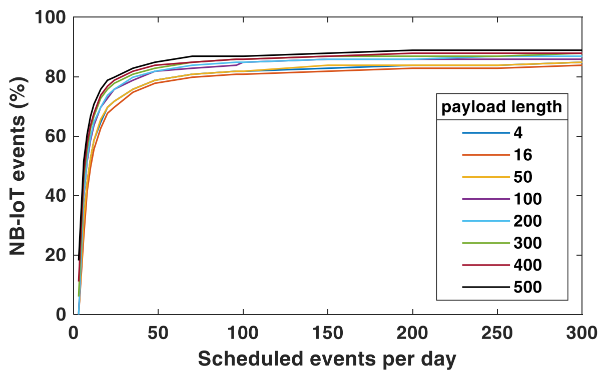



**FIGURE 11.** **Maximum number of NB-IoT events (as a percentage of the total) for which the hybrid solution is convenient over the single radio NB-IoT one, for different payload lengths.**

Moreover, from the results in Fig. 11, it is found that the breakpoint between the hybrid and single radio solution is not affected by the payload length for a number of scheduled events larger than 50. Instead, with fewer daily uploads, the payload contribution becomes more important, affecting the minimum value of NB-IoT events, which makes the single NB-IoT radio a preferable solution from the power consumption point of view. The system designer can evaluate the convenience of the single-radio with eq. (3), which requires

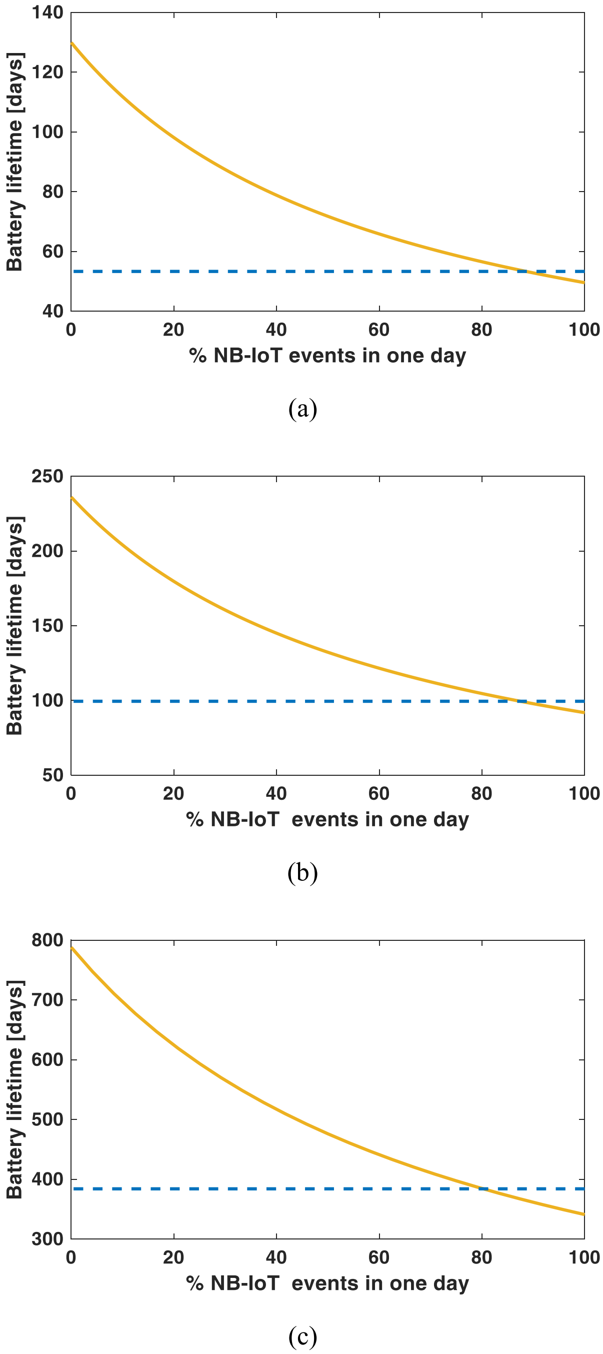



**FIGURE 12.** Battery life in the case of a hybrid solution Wi-Fi + NBIoT (solid line) with a payload of 500 bytes and different event time: (a) 8 min, (b) 15 min, and (c) 1 hour. The dashed line represents the single-radio NB-IoT level.

an a priori estimation of the fraction of daily time when the device operates in an area not covered by Wi-Fi networks.

## V. CONCLUSION

Wireless sensors for continuous monitoring are gaining a key role in the Internet of Things scenario. A radio section is mandatory in any WS to enable the connection to the Internet, with the ultimate goal to upload the data to a cloud service. Traditionally, sensor nodes rely on only one type of radio. In this paper, an innovative solution is presented, enhancing the portability of smart sensors with a hybrid transmission technology based on NB-IoT and Wi-Fi. The Wi-Fi is exploited primarily due to its lower power consumption, and NB-IoT is selected only when no Wi-Fi network is available. In this paper, the power consumption of the proposed solution in different environments is compared to the single-radio NB-IoT architecture. Several measurements have been carried out, considering multiple received powers and payload lengths. Since NB-IoT has proved to be sensitive to the payload size, particular attention should be paid to the amount of data transmitted, promoting on-board data pre-processing for minimum energy consumption.

Experimental results demonstrate that using the NB-IoT radio for both outdoor and indoor operations leads to at least one year of battery life, considering a 600 mAh capacity and 20 events/day. This result, while worsening the consumption profile of the traditional stand-alone Wi-Fi solution by a factor of about 2.5, allows the sensor to receive and transmit data even in the absence of Wi-Fi networks with a more than reasonable battery discharge time. Combining Wi-Fi for indoor and NB-IoT for outdoor operations improves overall energy consumption performance depending on the percentage of daily transmissions carried out with the NB-IoT radio. It has been demonstrated that beyond a certain percentage of NB-IoT events, there is no advantage in terms of power consumption of the hybrid solution compared to the NB-IoT single radio. The minimum number of NB-IoT events, which makes the single NB-IoT radio better than the hybrid solution in terms of power consumption, decreases with daily transmissions. If a higher number of NB-IoT uploads is required, since a long activity in an environment with no Wi-Fi coverage is expected, the single radio becomes the preferable solution. Anyhow, when the hybrid solution is fully exploited, the battery life almost doubled the NB-IoT single radio solution. Considering the percentage of NB-IoT daily events allows the system designer to choose the preferable solution to be adopted in the particular application.

At first glance, the hybrid solution has an impact on the device cost and size since two radio devices are required. Nevertheless, considering the actual prices, it has been shown that the hybrid solution exhibits a component cost close to the single radio NB-IoT. This study should stimulate the development of new devices combining these two technologies in a single chip, making the integrated management of the two radio protocols easier with a lower cost (at high production volumes) and size of the WS.

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