Duty-Cycled, Sub-GHz Wake-up Radio with -95dBm Sensitivity and Addressing Capability for Environmental Monitoring Applications

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***Abstract*— A novel approach for duty-cycled wake-up radios (WuRs) is proposed with focus on environmental monitoring applications involving wireless sensing devices left unattended in harsh conditions. In this scenario, a higher data latency (on the order of seconds or minutes) is potentially acceptable if significant improvements are achieved in terms of a) communication range, b) reliability, and c) energy-efficiency. The solution is solely based on off-the-shelf components with two main novelties implemented by software. First, the Receiver Bandwidth Filter of a commercial sub-GHz radio transceiver is configured with a small value typically not used in data communications (e.g., 9.5 kHz). Such action leads to a higher reliability of the WuR operation in outdoors where longer distances are involved and multiple signal interfering factors may be present. Second, the WuR addressing feature is achieved at the analog domain without requiring data decoding of any symbol. Nonetheless, more than 1,000 nodes can still be individually awoken with the proposed solution considering the 915MHz-ISM band. The preliminary empirical results from five outdoors sites involving more than 30 nodes show no false-positives and less than 3% of false-negative cases for distances higher than 225m and non line-of-sight (NLOS) and obstructed line-of-sight (OLOS) due to vegetation, rocks, and topography. By accepting a longer wake-up latency (e.g., 1 minute), the proposed solution which combines WuR and duty-cycling techniques can excel existing commercial WUR solutions in terms of energy-efficiency by more than one order of magnitude.**

Keywords*— *Wake-up Radio (WuR), Energy consumption, Signal-to-Noise Ratio (SNR), Receiver Bandwidth Filter, Wireless Sensor Networks (WSNs), Wireless Underground Communication, Internet of Things (IoT)

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I. Introduction

Modern low-power wireless communication involving sensing devices with constrained energy resources (e.g., battery-powered) typically employ duty-cycled Medium Access Control (MAC) protocols that allow radio modules to be powered-off for long periods of time while virtually providing the user-experience of being always available. However, the sensor node can still waste significant amount of energy if such radio module is activated multiple times during the day with no effective data communication (e.g., idle listening). Wake-up radio (WuR) systems have been recently proposed to mitigate this problem by allowing the data radios to be activated *on demand*, only when data communication with the node is necessary [1]. Typically, WuR receivers (WuRx) are always active in order to increase the responsiveness of the sensor nodes which makes the WuR solution very attractive to mission-critical applications such as industrial control where a node is expected to be awoken in less than 25ms [2]. To this end, WuRx modules must be significantly more energy-efficient compared to existing data radios used in Wireless Sensor Networks (WSNs). Accordingly, many of the recent WuRx implementations involve idle listening power consumption smaller than 100μW [2, 3], a value which is 1 or 2 orders of magnitude smaller than the idle listening power consumption of the majority of the WSN radio modules.

While the WuR approach seems to be a potential candidate to effectively replace all duty-cycled solutions, there are cases where the former and traditional solution is still more energy-efficient. A detailed study in [4] investigated the trade-offs between WuR and duty-cycling approaches. That study reports that when latency is not a critical factor of consideration and the duty-cycle is sufficiently small, the WuR solution may not be the best option. Another factor of consideration at the WuR design is related to the use of the communication channel. If a special hardware is necessary for the WuRx implementation, the solution is classified as out-of-band. But when the same radio module and its antenna are used for both WuRx role and regular data communication, such WuR solution is classified as in-band. The survey in [3] shows a slight dominance of out-of-band WuR solutions. Some WuR designs are indifferent regarding the use of the channel and support both in- and out-of-band operation. In general, while the latter mode has the disadvantage of the additional cost for the WuRx hardware, it provides an easy way of having the WuR feature integrated to virtually any wireless communication device. Typically, the WuRx module awakes the main radio system by raising an interrupt signal of the main controller which is in sleep or low-power mode. Alternatively, the WuRx can simply reset or power-cycle a legacy wireless node which can immediately start data communication after it is initialized. While this latter strategy adds latency to the solution, it is very easy to be implemented and almost "ready-to-use" with virtually any legacy system. Our proposed WuR design can operate with both in- and out-of-band channel modes. However, many aspects of the proposed design are mainly tailored for out-of-band operation since our WuR solution is also part of an ongoing effort of having aboveground WuR transmitter (WuTx) nodes that can wake-up underground nodes [5, 6].

In summary, the WuR technology has been adopted as an alternative for duty-cycling in order to (1) improve the responsiveness (i.e., smaller wake-up latency) of the sensor node while preserving acceptable energy consumption levels, (2) improve energy-efficiency, or (3) both of these goals, as reported in many cases in [3, 4]. However, few works at the WuR literature provide careful attention to *reliability* and *single-hop communication range*. According to one survey [3], only 4 out of 85 WuR implementations involve distances above 100m.The challenge associated to range extension for single-hop WuR was specifically highlighted in [7] where the authors achieved a 100m-range solution employing a sending power of +20dBm with a packet error rate (PER) of 5%. That same solution was later investigated with a deeper reliability analysis and it became clear the critical impact of the height of the WuR devices in the communication performance even for a free-space and LOS scenario [8]. Such range limitations may explain the abundance of WuR research associated with multi-hop protocols which is another way of addressing the distance challenge [3].

In this study, we target star/single-hop network topology for outdoors environmental monitoring with distances higher than 200m under critical non line-of-sight (NLOS) and obstructed line-of-sight (OLOS) conditions and heavy RF interference. The main design goal behind the proposed WuR system is to achieve exceptional reliability while maintaining the added energy due to the WuRx circuitry reasonably small (e.g., up to 100μW). To this end, this WuR solution mainly sacrifices its wake-up latency which is a decision that deviates from typical WuR strategies [1-3]. In terms of classification [3], this is an active RF-based (ISM-915-MHz) *duty-cycled* WuRx solution with sensitivity better than -95dBm and comprised of off-the-shelf components. It supports both in-band and out-of-band channel operations and it is possible to wake-up an individual node, a group of nodes, or the entire network. Successful results involving 5 different outdoors sites during two years of experiments are discussed.

The rest of this paper is organized as follows: in Section II, the design strategy is discussed where we highlight the reasons why we believe that the active WuRx is the proper answer for many environment monitoring applications. Section III is the first core part of this paper where one novelty is presented: the configuration of the RX Bandwidth Filter of the radio transceiver to small values that are typically avoided for data communication. In Section IV, the second core part of our investigation – a novel WuR signal detection algorithm – is presented with the proposed WuR addressing scheme which is based on the carrier-frequency value. In Section V, the architecture for long-term deployments is presented and related results are discussed. Finally, the lessons from the experiments and the future work are discussed in Section VI.

II. Design Strategy

A. Application Characteristics

This WuR design is part of an ongoing project [9] that started in 2009 which aims real-time in-situ soil moisture data collection used as part of the validation data for at least two NASA missions associated to the estimation of soil moisture using microwaves: Airborne Microwave Observation of Subcanopy and Subsurface Mission (AirMOSS) and Soil Moisture Active Passive (SMAP). Due to the characteristics of such application and associated costs, it is important to have a medium number of sensor nodes covering large areas (i.e., sparse WSNs). Typically, each of these outdoor sites has between 15 to 25 sensor locations, each location with a plurality of soil sensors. Since 2011, the network architecture is based on IEEE 802.15.4 nodes [10] that follow a strict star-topology implemented by a cross-layer solution that we developed [11]. Since those nodes are installed in remote areas (including sites at the Arctic Circle – currently operational) and are left unattended for long periods of time, special attention to the reliability/energy of the nodes is paramount [12].

The WuR feature was recently introduced at the above bigger project as part of an effort of having intelligent networks/sensor nodes where machine-learning based decisions replace fixed sampling schedules (e.g., measurements every 20 minutes). With such solution, two traditionally conflicting goals are expected to be strategically balanced: to increase the sensor nodes' battery lifetime and to improve the data quality. WuR technology is a key-component for such plan because it provides a way to activate nodes *on demand* or due to certain non-controlled events (e.g., rainfall).

B. Non- Radio Frequency (RF) Options

Our first step toward the WuR design was to investigate the possibility of employing non-RF solutions, aiming mitigating interference issues. A relative quick literature review revealed the high risks associated with the adoption of acoustic and ultrasonic waves solutions for NLOS and BLOS scenarios, in particular for target inter-node distances of more than 200m. Moreover, the associated energy costs were significantly higher than some reported RF-based WuR solutions at the literature. Magnetic-Induction (MI) was also investigated since obstacles, such as rocks and trees, do not significantly impact the MI-communication channel [6]. However, our MI signal attenuation model for over-the-air (OTA) and soil medium showed that the energy costs and the hardware complexity at the receiver side were impacting factors in comparison with existing RF-based solutions and associated potential interference challenges.

C. *Passive vs. Active Wake-up Receiver*

In general, the term *passive* at the WuR context means that the WuRx device will be able to be powered by the energy available at the communication channel. Passive RFID circuits are examples of the application of similar technology. Nonetheless, even assuming ideal LOS between WuTx and WuRx nodes, such form of energy harvesting is typically not practical for distances higher than 10m. The following example illustrates this challenge: assume a 900MHz continuous-wave (CW) being ideally transmitted at +20dBm (100mW) and no gain or loss at circuits/cables/antennas. Also, assume that WuRx alone has activation energy-consumption of 10µJ (i.e., 10µW power-consumption during 1 second). How much time it would take to "wake-up" this node considering 100m-distance and also assuming ideal conditions for the energy-reservoir at the receiver side? By applying the Friis' free-space transmission formula [13] with G_{TX}=G_{RX}=1, we have:

$$P_{RX} = \frac{P_{TX} \cdot G_{TX} \cdot G_{RX} \cdot \lambda^2}{(4\pi \cdot d)^2} = \frac{(0.1)\cdot(1)\cdot(1)\cdot\left(\frac{3E8}{9E8}\right)^2}{(4\pi \cdot 100)^2} \cong 7nW \quad (1)$$

where *d* is the distance in [m], λ is signal wavelength and the wave speed is set to $3*10^8$ m/s. In order to achieve 10µJ, such ideal energy-reservoir at the passive WuR circuitry would have to wait at least 1,428s or 23.8 minutes. By changing *d* to 5m, the WuR activation time would change to a more practical value of 3.6s. Additional investigation of passive WuR solutions [3] confirms similar findings regarding the limitations of the communication range.

As previously discussed, few WuR works report communication range above 100m and all the reported ones involve *active* WuRx systems. At Table I, some of these studies are listed with their maximum communication range, some test conditions, and energy consumption for 24h-period (without waking-up). At the end of that table, our achievements in this work are also listed – details are later discussed in Section V.

D. *Wake-up receiver built with off-the-shelf components*

One critical design goal was to reach a functional WuR prototype is less than 6 months. Therefore, chip fabrication as in [16] was opted-out. Our next step was to look for radio transceivers with such WuR functionality. Our expectations were to achieve a baseline for comparison with potential of being customized to improve energy-efficiency and communication range. Our selected module was the CC1200 radio transceiver [17] which has a special superheterodyne configuration with two mixers (in-phase, in-quadrature) thus providing 56dB typical image-rejection. The CC1200 device is mainly intended to the ISM and Short Range Device (SRD) bands at 164-190MHz, 410-475MHz, and 820-950MHz.

TABLE I. ACTIVE WURX: COMMUNICATION RANGE VS. ENERGY CONSUMPTION

Ref.	Method	Conditions	Sensitivity	Range	WuTx Pwr	WuRx Pwr	24h-energy
[14]	RF-ISM 2.4GHz	LOS [a]	-83 dBm	120 m	NA	1620 µW	140.0 J
[15]	Acoustic 85 kHz	LOS [a]	NA	240 m	100 mW	8.1 µW	0.7 J
[16]	RF-ISM 868MHz	LOS [a]	-71 dBm	304 m	4.4 mW	2.4 µW	0.2 J
This work	RF-ISM 915MHz	NLOS / OLOS [b] 8s-interval	-95 dBm [b]	225 m	25.1 mW	366.7 µW	31.7 J
This work	RF-ISM 915MHz	NLOS / OLOS [b] 16s-interval	-95 dBm [b]	225 m	25.1 mW	181.0 µW	15.6 J
This work	RF-ISM 915MHz	NLOS / OLOS [b] 30s-interval	-95 dBm [b]	225 m	25.1 mW	93.2 µW	8.2 J

a. The work does not explicitly mention the conditions for the test involving the maximum range.

b. Non line-of-sight (NLOS) and Obstructed line-of-sight (OLOS) are typical in our application [9].

c. The measured sensitivity performed in the lab with attenuators is -105 dBm where we achieved false-positives rate of 0 and false-negatives rate <1%.

For the tests discussed in this work, we have used the U.S. ISM-915-MHz band which involves frequencies from 902 to 928 MHz. Most of our tests were performed at 906-907 MHz range just for configuration convenience. CC1200 provides a native functionality called Enhanced Wake-On-Radio (eWOR) which is basically an automatic duty-cycling approach (no intervention from a microcontroller is required) that runs off an ultra-low-power RC oscillator. When eWOR is combined with another CC1200 feature called RX Sniff Mode, it is possible to achieve a solution like many of the reported WuRx implementations. In this case, the wake-up is achieved by few preamble bits. Therefore, a CC1200-based solution belongs to a WuRx category of devices rarely mentioned at the literature: duty-cycled WuR [3]. Clearly, the main trade-off involves energy-efficiency and wake-up latency. We eventually have not employed these native CC1200 features but we borrowed the duty-cycling idea for the WuR operation.

E. *Reliability: false-positives and false-negatives*

Our time-proven energy-efficient and robust WSN solution for environmental monitoring employs an energy-deterministic approach based on non-rechargeable batteries, supercapacitors, and a time-slot application protocol called BETS [11, 12]. Therefore, care was taken in order to avoid that the addition of the WuR functionality deteriorates the performance of the current duty-cycled WSN solution. This was one aspect that called attention in our investigation: the lack of reliability details in many WuR papers. Some exceptions, as in [1, 8, 14-16], report some form of *false-negative*s metrics associated with wake-up calls not captured by the node. Even more difficult is to find metrics for *false-positives*, as reported in [15], when the node wrongly wakes-up without a genuine wake-up call. For our application, a false-negative is less important than a false-positive because the former causes an additional latency to wake-up a node, which is not a critical aspect for our specific application. However, a false-positive event causes the sensor node to be activated, to take measurements and to transmit the data using the regular communication channel. This can impose serious energy-penalties in a system that controls the lifetime of the batteries used by the nodes. During our preliminary tests with the native CC1200 WuR solution, we were not able to determine if false-positives ever occurred. Preliminary lab and campus tests showed no evidence of this issue and this may be explained by the efficiency of the CC1200's preamble addressing scheme. On the other hand, false-negatives were very high (38%) for both 150 and 200m cases shown in Fig.1. These preliminary results indicate that the native CC1200 solution will not be able to address our main design goal of achieving up to 200m-single-hop distance for NLOS/OLOS scenarios.

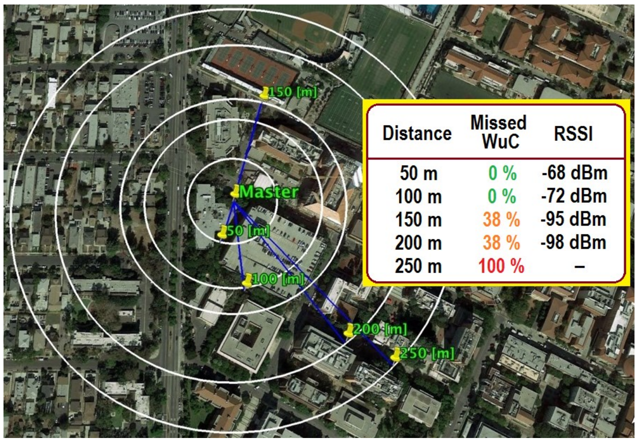

Fig. 1. CC1200 RF transceiver "Sniff Mode" tests at the campus of University of Southern Califonia (USC). The "Master" location (WuTx node) is fixed and the WuRx node is mobile. The Wake-up Call (WuC) performance of this off-the-shelf WuR solution is critically degraded for distances above 100m and non-line-of-sight scenarios. This fact is also indicated by the Received Signal Strength Indicator (RSSI) data. The transmit power level was +14dBm, antenna-height was around 1.5m and generic 2-dBi antennas were employed.

F. Summary of the design goals

After few months of investigation, the WuR system design criteria were determined, as listed below. One can clearly note that a high wake-up latency (60s) is traded in favor of obtaining high communication range for NLOS/OLOS scenarios (200m) while consuming fair energy (20 J / day):

1. Minimum 200 [m] distance between the site controller (WuTx) and sensor nodes (WuRx).
2. Added daily energy consumption due to WuRx must be smaller than 20 J.
3. Wake-up latency must be smaller than 1 minute.
4. Wake-up likelihood must be higher than 99%.
5. Implementation must be feasible in 6 months or less.

III. The Impact of Small Bandwidth for the Rx Filter

The preliminary USC tests provided an important information: at 150m, the wake-up failure rate (i.e., false-negatives) was 38% for received signal strength (RSSI) of -95dBm. However, by investigating the CC1200 datasheet, one can observe that the radio receiver still has sensitivity for signals at -122dBm and 1.2 kbps data rate. While the implementation details of the Sniff Mode of the chip are not available, potentially the Wake-up Call (WuC) based on preamble bits is associated with a very low data rate configuration. Therefore, a potential explanation for the 38% missed WuCs is that the external signal interference significantly contributes to a noise-floor level close to -95dBm (i.e., significantly degrading the SNR). A high transmit power level would potentially mitigate the challenge of reliability/range but this simple solution may be prohibited by wireless regulations and also associated strong energy penalties.

The above challenge has some similarities with a typical problem faced by physicists: the need of measuring very small signals "buried" in noise. The solution comes in the form of a lock-in amplifier (LIA) instrumentation which is basically the same superheterodyne circuit already used in radio receivers but with a fundamental difference: no up/down-conversion or, in other words, no Intermediate Frequency (IF). The accuracy of the LIA readings is associated with the selection of larger values for the "time-base" of a low-pass filter typically located after the mixer component. Such LIA filter function clearly has similarities with the Receiver Bandwidth Filter (RBwF) used in modern radio receivers. Our previous work with LIA circuits and Magnetic-Induction communication links [6] provided the foundation for testing the following:

> ***Hypothesis****: If no data modulation is employed (i.e., continuous-wave – CW mode) and the RBwF is set to its minimum possible value (e.g., few kHz), then the SNR for that CW signal representing the WuC would be significantly boosted.*

The first part of the hypothesis establishes conditions where virtually no or minimal bandwidth is necessary, and this is done by simply avoiding data modulation. While the WuC in such mode is still a form of modulation (i.e., On-Off Keying – OOK), no data communication, or even the WuR addressing scheme, will be performed with the magnitude manipulation of the CW signal. The second part of the hypothesis is the ultimate action expected by this high-Q filter: eliminate many frequency components from both internal noise and external interferences. With such RBwF filtering, the expectation is to have a smaller perceived noise level or, alternatively, an SNR increase or boost. To test the above hypothesis, no hardware modification is necessary, it is only a matter of properly performing the CC1200 configuration via MCU and SPI interface (note: for our preliminary tests, a Raspberry Pi computer was used in place of the MCU).

The first part of this investigation does not require the WuTx node. Rather than a typical antenna, a 50Ω-resistive load is inserted at the antenna connector of the WuRx node with the expectation of not capturing strong and transitory external signals at this moment. The operating frequency is set to 907.000 MHz and different values for RBwF are configured including the smallest one (9.5 kHz) and perceived RSSI values are tabulated in Table II. As shown in that table, the internal noise-floor level decreases with smaller RBwF values which is not a surprise since noise-figure is proportional to the signal bandwidth. While there is not significant difference in adopting RBwF 37.9 kHz or 9.5 kHz, there is a compelling reason to select the smallest value possible: a higher number of address IDs for the WuRx nodes in a network, to be discussed soon.

TABLE II. INTERNAL NOISE FOR DIFFERENT VALUES OF RECEIVER BANDWIDTH FILTER OF CC1200 RF TRANSCEIVER

Receiver Bandwidth Filter	No input signal RSSI
208.3 kHz	-116 dBm
185.2 kHz	-117 dBm
151.5 kHz	-118 dBm
104.2 kHz	-121 dBm
69.4 kHz	-122 dBm
37.9 kHz	-125 dBm
9.5 kHz [a]	-126 dBm

a. Value selected for the proposed WuRx solution.

The next step at the investigation is to verify if the *external* noise or interference is also significantly reduced after the receiver filter. This bandpass filter is located after the mixer module and before the ADC stage of the CC1200 receiver circuitry. The signal strength perceived as RSSI values is captured just before the ADC. Therefore, the expectation is also to observe improvements when external noise is involved. To test this hypothesis, we performed tests in an urban environment: the Ferndell Trail in Griffith Park (Los Angeles, CA). This site has significant amount of vegetation and trees and also the presence of visitors passing very close to the WuR nodes under investigation. As shown, in Fig. 2, these nodes were placed along the trail.

Fig. 2. WuR nodes in their first prototype version: Raspberry Pi connected to CC1200 radio transceivers operating at 907.0 MHz. Our special software-configuration for these transceivers is not a traditional one that could be practical for regular data communication due to the very small bandwidth (e.g., 9.5 kHz). Nonetheless, this provision can boost the WuR-SNR thus improving the WuR performance. In this experiment at Ferndell Trail in Griffith Park (Los Angeles, CA), it is tested if such configuration can be a potential solution for WuR nodes in relation to reliability and communication range under different levels of signal interference and non line-of-sight and presence of obstacles.

In addition to using the native WuR solution from Texas Instruments which uses an evaluation control board from the manufacturer to control the CC1200 modules, we customized a solution where the CC1200 are SPI-connected to Raspberry Pi computers. For this latter case, the WuTx node was set with transmit power level of 14dBm, and CW operation at 907.0 MHz. The WuRx node had its RBwF configured to 9.5 kHz and the software at the computer regularly checks the RSSI level at CC1200 (i.e., duty-cycle operation). A valid WuC was defined at the computer program as a temporal sequence of RSSI values above a certain threshold (e.g., -98dBm) without interruptions or drops below that threshold for a certain amount of time (e.g., 200ms). The complete algorithm is discussed at Section IV. While both options, evaluation board from the manufacturer and our customized solution with Raspberry Pi used exactly the same hardware, the key-differences are related to the configuration of the CC1200 modules. Therefore, our expectations were that the latter "modified" solution would excel the "regular" former option, which actually occurred. The results of these Ferndell Trail experiments are shown in Fig. 3 where the locations of the tests are highlighted. Note that the WuTx node has a fixed location and the WuRx node (with options "modified" and "regular") is placed at different points along the trail.

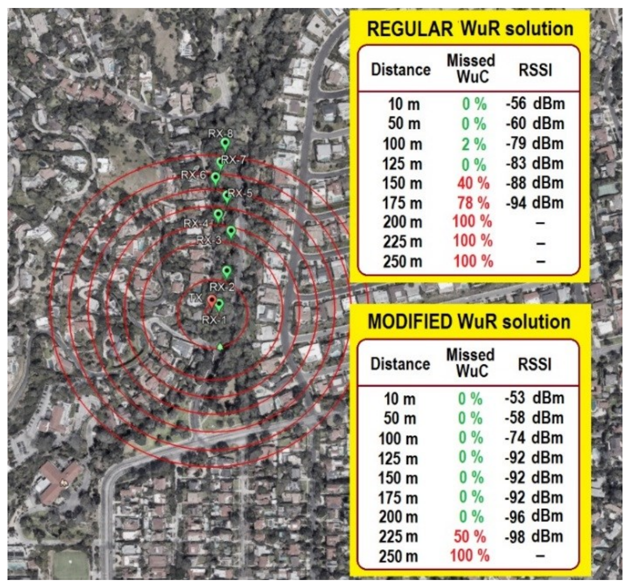

Fig. 3. Results from the Ferndell Trail experiments showing that the configuration of the Receiver Bandwidth Filter with a very small value (e.g., 9.5 kHz) has a significant impact on the WuR performance in relation to reliable communication for longer diatnces and/or NLOS/BLOS scenarios. Note that the WuR hardware for the regular and modified configuration was the same.

IV. SIGNAL STRENGTH-BASED WAKE-UP DETECTION

With the knowledge that it is possible to extend the communication range by simply reconfiguring the bandwidth of the receiver bandpass filter (RBwF) and using the signal strength of the CW-based WuC signal, the next step is to provide a way to minimize or eliminate false-positives. Moreover, without the possibility of a more sophisticated modulation to achieve WuR-ID addressing due to the very small signal bandwidth, an alternative addressing scheme is necessary.

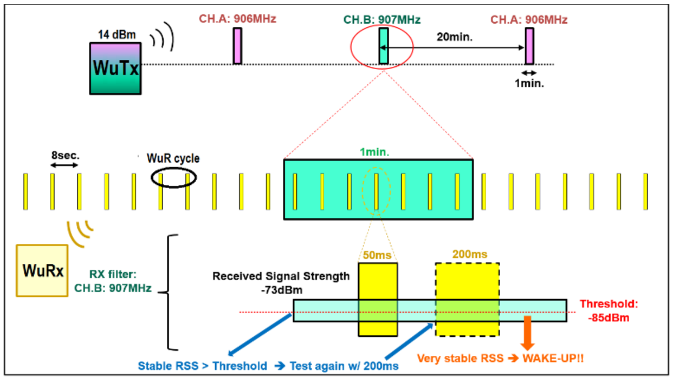

Fig. 4. Proposed duty-cycled WuR algorithm. First, the WuRx addressing scheme is implemented by software-configuring the radio transceiver with a certain pre-determined frequency. In our experiments, such "channels" can be interspaced by small values, such as 25 kHz. Each WuR channel can be assigned to an individual node or a group of nodes. Second, if an existing duty-cycled WSN solution has a certain schedule (e.g., 20min.), the WuTx can start each operational cycle by waking up certain nodes or the overall network. The wake-up call (WuC) can last for several seconds if necessary. The third part of the algorithm is implemented at the receiver side and it is based on signal strength detection. If the WuC signal strength stays continuously above a certain threshold (e.g., -85dBm) for a sufficient amount of time (e.g., 50ms), a second and longer verification step (e.g., 200ms) makes another check in order to confirm that the received signal is a real WuC and not a false-positive before waking-up the node. In our implementation of this algorithm at different sites, we achieved 0% of false-positives thus empirically confirming the effectiveness of the proposed algorithm for environmental applications.

These challenges were partially addressed at the previous tests at Ferndell Trail. However, false positives can still occur if the addressing scheme is not very robust. The overall algorithm of our improved and final WuR solution is illustrated in Fig. 4 which also provides detailed explanation. The main points are:

a) The addressing scheme is solved with the use of different frequencies centered at what we call WuR-channel. Each channel can be very closely interspaced (e.g., 25 kHz), thus allowing individual- and group-addressing in typical ISM bands.

b) The WuC detection is implemented by checking the stability of the received signal strength (RSS) above a certain threshold. The rationale here is that wireless regulations usually impose ways to avoid wireless devices to monopolize the use of frequency bands for long time. The *on-time* of the WuTx CW-signal is long enough for this detection scheme, but it cannot be so long to the point of violating regulations which is an aspect to be considered in the WuR design.

c) Since multiple sources of interference may be present, false-positives are a potential risk for this design. Moreover, since it is assumed no clock-synchronization at the network, small clock-drifts (e.g., 10 kHz) can cause the WuC waking-up the non-intended WuRx node which has a WuR-channel very close to the target WuRx node(s). Such challenges were addressed by checking the continuously stability of the WuC signal in two stages. If false-positives still occur, it is possible to increase the interspace between WuR channels. In our experiments, such modification was not necessary.

Another round of outdoor experiments in semi-urban area (Pullman, WA) was performed. The goal was to test the improved algorithm shown in Fig. 4 considering significant topography differences. The results were pretty similar to the previous experiments at Ferndell Trail and are omitted for convenience. The only important highlight is that the furthest node (210m-distance) had perfect WuR reliability performance even under NLOS conditions and terrain-height differences higher than 12m. At this location, the (successful) perceived WuR-RSSI was -89dBm. However, it is worth to highlight that it was not possible to have any 915-MHz radio solution working at the same location, including the same CC1200 transceiver with its regular configuration for data communication. Such findings are very important due to the potential applicability of the proposed WuR solution beyond single-hop topologies. For instance, it may be possible to use such kind of boosted WuC to single-hop wake-up cluster-head nodes or Access Points (APs) from a distant central point where a controller/gateway node is located. Such provision would favor a balanced workload distribution of the role of cluster-heads (or similar function) in ad-hoc wireless networks.

V. EMPIRICAL RESULTS AND DISCUSSION

In March 2019, the WuR moves from the prototype phase to the massive implementation in our SoilSCAPE project [9] involving multiple sites and more than 150 sensor locations. To this end, additional and long-term experiments were necessary and two sites (Jackson, CA and Millbrook, NY) were selected as pilot ones for the WuR deployment. In Fig. 5, we have two variants of the WuRx node: the top device is an out-of-band solution deployed as *add-on* board to a legacy WSN node. The other implementation at the bottom is a hybrid version that supports both in- and out-of-band operations with a single antenna if both channels are ISM-915MHz. This latter device is our WSN sensor node with integrated WuRx circuitry. Both versions are based on the CC1200 sub-GHz radio transceiver [17]. In all cases, a low-power MCU is dedicated to the implementation of the WuRx algorithm shown in Fig. 4.

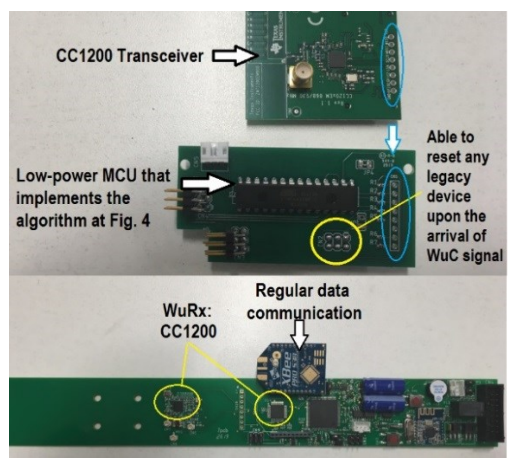

Fig. 5. Implementation of the WuRx solution using off-the-shelf components. Top: Out-of-band solution which is virtually compatible with any legacy device at the network. Bottom: In- and out-of-band WuRx solution. The experiments in Section V were performed with the top WuRx implementation.

The experimental setup for these deployments is relatively simple since no critical integration with the legacy WSN nodes will be required: the WuRX just resets the main MCU of the WSN node upon detection of the WuC. The default behavior of these nodes is to take measurements and send data to the main controller node in a single-hop fashion. For preliminary lab tests, we tested the efficiency of the WuR algorithm by configuring multiple nodes with channels A (906.975MHz), B (907.000MHz), and C (907.025MHz). The multiple long-terms sessions summed dozens of hours with WuTx following a 20min-schedule. An impressing 0% rate for false-positives/negatives was achieved. At the field, false-positives did not occur and they are not explicitly reported at the tables with the results. However, the false-negatives rate (i.e., not being able to wake-up a node) slightly increases to approximately 3% and all the outlier cases involved nodes deployed with NLOS/OLOS conditions. This was expected based on the results at Fig. 3 where missed WuCs only occurred at the 225m-distance case. In that case at the Ferndell Trail, the reported RSSI from the CC1200 chip was -98dBm. This was an indication that our solution has a potential reliable sensitivity around -90dBm and -96dBm. Based on the analysis of all our experiments, we determined a sensitivity of -95dBm with worst-cases constrained to less than 3% of false-negatives rate.

At the Tonzi site (38°25’51.27” N, 120°57’57.36” W), we have used two frequencies (906.0 and 907.0 MHz) in order to wake-up two groups of nodes. Since that terrain was not critical in terms of topography, we decided to use a WuC signal strength threshold of -85dBm. However, the signal attenuation due to the trees and the high-level of RF interference in this specific site were underestimated in our calculations of the above threshold. After getting the results, we learned that the temporary interference on a relatively strong WuC -75dBm signal can make the RSSI detection drop below -85dBm. Even few milliseconds of such drop are enough for the WuR algorithm to discard the WuC as non-valid. Such level of interference from dozens of existing instruments in this site was clearly observed with a portable spectrum analyzer. The consequence is the lower reliability for the WuR solution which is observed in Fig. 6.

The red marks at Fig. 6 do not mean false-positives but they represent the event when a node was not awoken at the expected moment in time (i.e., missed WuC). In this case, if more than 1h elapses, the default behavior of the WSN node is to contact the controller node (marked as WuTx) – an automatic provision even without the presence of WuCs. In this way, the node communicates at the “wrong” cycle (i.e., out of sync). Recognizing the improper initial definition of the WuC RSS-threshold, we selected the node #7 to test another option: -98dBm value. The vertical dash line represents the moment of this modification. As soon as this change was done, the node #7 had an ideal WuR performance with no false-negatives. This was already the case for nodes #1 and #2 even without the mentioned modification. A potential explanation is that for those nodes #1 and #2, the perceived WuC-RSS was strong enough to not be affected by the nearby RF interference. This experience showed the importance of developing an adaptive strategy for the WuC RSS detection which is still a work in progress.

For the next deployment, we decided to establish the value of -98dBm as the standard WuC RSS-threshold for all nodes. Our main concern was that such decision could increase the likelihood of false-negatives which would impose a huge energy penalty. The selected site for this test is located at the Cary Institute of Ecosystem Studies, Millbrook, NY (38°25’51.27” N, 120°57’57.36” W). Although the level of RF interference was not critical in this site compared to Tonzi site, the topography of the terrain is definitely a challenge.

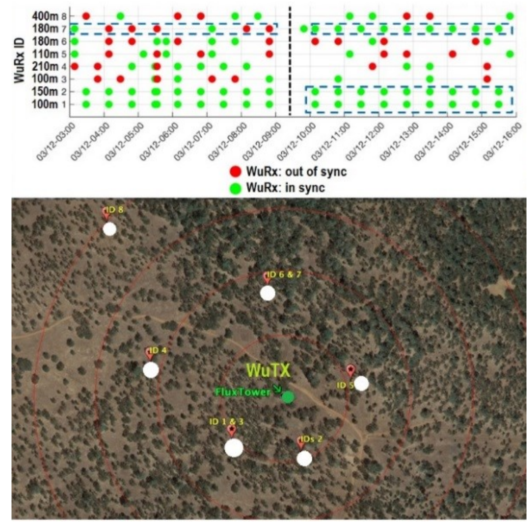

Fig. 6. Initial WuRx experiments at Tonzi Ranch (Jackson, CA), a site with dozens of scientific instruments and a scenario with high RF interference. By initially setting the WuC-RSS threshold to -85dBm, many WuRx were not able to properly operate even if the WuC signal has a stronger RSS than -85dBm which was the case of node #7. After this analysis, the threshold of node #7 was changed to -98dBm. As a result, no false positives/negatives for that WuRx node were observed. Such WuR configuration with -98dBm threshold became the default one for the deployments in this project.

As shown in Fig. 7, that node position (ID-8) at Millbrook site is particularly a challenge for the WuR performance. This NLOS scenario involves a critical height difference of 9.5m and 165m-distance to the WuTx node. Two WuR nodes are placed at this location. Another location in this site (not shown in this figure), is 225m away from the WuTx node and it is above the level of this node by 7.5m. The WuR design in this work aims specifically such critical single-hop scenarios.

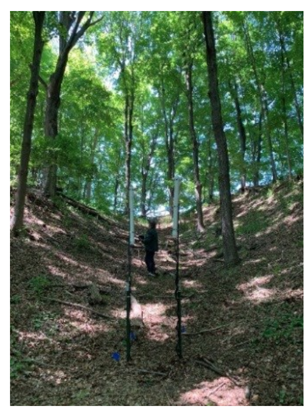

Fig. 7. Implementation of the WuRx solution at the Millbrook site. This node location exemplifies the challenges associated with environmental monitoring applications where sensor nodes are typically left unattended for very long periods of time (e.g., 15 months). This is a NLOS case where the WuTx node is 165m away and 9.5m above the level of these two WuRx nodes.

The Millbrook site has 16 WSN nodes, including the main controller (star-topology) which also has the WuTx role. All sensor nodes are powered by non-rechargeable batteries with a realistic lifetime of at least 15 months [11, 12] and each one has 4 soil probes attached. The main controller is the only node powered by a rechargeable battery connected to a solar panel. This node also has an attached weather station and it is responsible for the 3G/4G connectivity to the cloud. These nodes are deployed in 10 different locations ("ID-" label at Fig. 8) and some nodes have LOS with WuTx and some do not. The deployment layout and measured WuC-RSS levels via WuRx and portable Spectrum Analyzer (SA) are shown in Fig. 8. For this site, we have implemented the -98dBm WuC-RSS threshold configuration and we have achieved satisfactory success for the WuR operation: so far, 0% false-positives and less than 2% false-negatives on the average for all nodes. A WuRx node is not always active listening for WuCs: we have implemented duty-cycling for WuR operation. When WuTx wants to wake a node, it activates CW at a specific frequency corresponding to a certain node, a group of nodes, or the entire network. In our experiments, WuC-CW signal is active during 30 to 60s, but this value can be greatly reduced considering the observed effectiveness of this WuR solution. From the WuRx perspective, the node checks the channel every 8s during 50ms. All those values can be easily changed in software but, so far, this configuration provided excellent results.

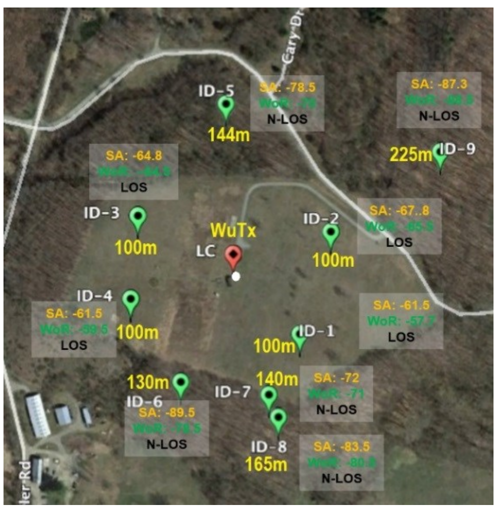

Fig. 8. Topology of the network at the Millbrook site. The main challenge in this site related to the WuR performance is related to the terrain topography and obstacles (trees and rocks). The best results in this worked were achieved in this site where all WuRx nodes use WuC-RSS threshold of -98dBm. Even with so small values, no case of false-positives were observed.

VI. Conclusions

The proposed WuR solution addresses cases where sensor nodes are deployed in outdoors under very complex circumstances in terms of wireless channel (NLOS, interference, long distances, etc.). In this work, we have implemented WuR devices with off-the-shelf components and using ISM-915-MHz band. This provision makes the solution an easy WuR option to deploy. The main novelties of the solution are: a) the non-traditional bandwidth configuration of the receiver filter, b) the detection of the wake-up signal based on the temporal stability of its signal strength above a certain threshold (e.g., -98dBm), and c) the addressing scheme based on the frequency of the WuC-CW signal. The empirical results confirm the high reliability level of the solution for complex outdoor scenarios (NLOS/BLOS) and distances up 200m while maintaining the energy consumption almost one order of magnitude smaller than many commercial solutions. This possibility is mainly feasible due to the integration of duty-cycling combined to WuR. The next steps of this project involve the development of the theoretical model to support some aspects of the proposed WuR algorithm.

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