Comparing Low Power Listening Techniques with Wake-up Receiver Technology

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***Abstract*—One of the major challenges in wireless sensor networks is in reducing power consumption of the individual motes while not degrading the functionality of the network as a whole. With wireless sensor technology becoming more wide spread and larger deployments of this technology being rolled out post deployment issues such as battery replacements become a bigger issue. Reducing power consumption is essential in situations where it is infeasible or impractical to frequently replace batteries. Reducing the power consumption of the motes to a level where batteries can last years or where ideally to levels where energy scavenging becomes more feasible, resulting in battery-less operation of wireless networks, is a major research challenge. One of the main energy consumers on a wireless mote is the radio transceiver. Current approaches using low power listening techniques to reduce mote power while maintaining meshing capabilities and this paper compares the state of the art in low power listening (BOX-MAC 1 and 2) with the latest in commercially available wake up radio technology (Austria Microsystems (AMS) AS3933) to determine which approach is more efficient from an energy consumption view. A theoretical approach has been taken to compare achievable lifetimes of motes under different traffic situations using both Low Power Listening (LPL) methods and Wake up Receivers (WUR). This is then compared against empirical data. As this paper shows, when considering power draw of radios in different configurations, WURs consume up to 20 times less power compared to techniques, thereby enabling indoor energy harvesting (EH) solutions to become practical.**

Keywords*—*LPL; Wakeup Radio; BOX-MAC; BMAC; XMAC; Wireless sensor networks

I. Introduction

One of the main challenges in Wireless sensor networks (WSNs) to date is post deployment lifetime of the motes [8]. Batteries are often used to supply power to the wireless motes as supplying a constant power source would be infeasible, for example in outdoor locations where power infrastructure is non-existent [14].

Moreover, regularly changing the batteries would be impractical and also expensive, while the costs of the batteries are relatively cheap (sub 1 euro) the cost of maintenance staffs time to carry out the work is not. Because of this, reducing power consumption by as much as possible to either increase the time between battery changes or make the devices energy harvesting compatible is an important research topic.

Often, the most resource hungry device in a mote, for a WSN is the radio, consuming around 19mA in receive mode [12]; so, much work is put into reducing its on time. Two ways in which power used by the radio may be reduced are either using a duty-cycling media access control (MAC) protocol, or, using a low-power wakeup radio (WUR) [4], which consumes minute amounts of power while still being in a constant active or listening state.

Low power listening (LPL) protocols reduce power consumption by putting the radio into sleep mode with regular intervals in which it will wake up to sample the channel for activity. This introduces latency into the network which in some cases would be unacceptable ,e.g., a system controlling a solar panel or wind turbine where systems need to be shut down to prevent damage to them in a timely fashion.

Despite the advantages that WURs may offer their uptake in WSN applications to date has been limited, possibly due to them having lower receive sensitivities when compared with conventional radio frequency (RF) radios as well as much reduced range. While there are designs available that consume a few microwatts [1] while being able to receive data, their benefits vs. traditional low power techniques are still uncertain. If validated, WUR could pave the way for much longer WSN node lifetime.

I. Demirkol [4] have performed a previous comparison between low power listening modes and wake-up radios, they do not include a comparison of newer, more efficient, low-power listening protocols such as BOX-MAC [10]. Amre El-Hoiydi in [5] discusses that the development challenge of creating a WUR that consumes tens of µA necessitates the further development of protocols that rely on the main radio.

W.S. Wang et al. [15] discuss power levels that are attainable from various indoor based energy harvesting solutions. They determine that for a single solar cell in an indoor location, the maximum power attainable is 151.6 µW. This paper uses analytical work to show that with such a constrained power budget, using LPL methods would be insufficient for use in battery-less operation.

The rest of the paper is ordered as follows. Section II covers background work in the area of LPL MAC protocols as well as advances in WUR technologies, it also includes the limitations of wake up receivers compared to traditional radios utilising LPL methods. Section III will cover the analytical work done. Section IV outlines the experimental setup used to verify the theoretical work carried out in Section III. The results of analytical and empirical work are described in Section V. Conclusions are presented in Section VI and future work the authors wish to carry out in this space is listed in Section VII.

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II. BACKGROUND WORK

A. Low power listening modes

The need to reduce power consumption for a device lead to the creation of LPL methods, indeed, if the radio is left on in listening mode constantly, the battery powering the mote could be drained in as little as 3 days [11]. Because of this, much research has been done on proposing new methods to reduce the duty cycle of radios. Early work in this field relied solely on information from a single layer in the protocol stack ,e.g., sensor-MAC(S-MAC) [16], Berkeley-MAC (B-MAC) [13], X-MAC [3], whereas newer techniques are starting to rely on information from multiple layers to achieve better efficiencies, example, BOX-MAC and WiseMAC [5].

1) S-MAC: S-MAC was designed with the reduction of energy consumption as its primary goal, other aims for the protocol were to provide good scalability and collision avoidance, and these secondary goals are achieved through the use of a combined scheduling and contention scheme. S-MAC is based on 802.11 MAC protocols. The authors of S-MAC identified four major sources of energy waste.

Firstly, collision occurs when corrupted packets that are discarded and need to be re-transmitted, this also has the unwanted effect of increasing latency in the network. Overhearing is when a node receives a packet that it is not meant to. Thirdly, the overhead that is required for control packets, and finally, idle listening of the channel can consume 50%+ of the energy required in receive mode [16]. S-MAC was created to tackle these issues; it relies mainly on the physical layer and has a fixed listening period of 115ms with a variable sleep period between checks to achieve different values for duty cycle [13].

2) B-MAC: B-MAC was created with the goal of increasing packet delivery rates, throughput, latency, and energy consumption compared to S-MAC. B-MAC uses clear channel assessment (CCA) and packet back offs for channel arbitration. Reliability is achieved through link layer acknowledgements, with LPL being used for low power communications. While S-MAC includes network and organization within the protocol, B-MAC does not include these functionalities (e.g., synchronization and routing), leaving it up to higher levels to implement such things. B-MAC is the default MAC protocol used by TinyOS and relies on the physical layer for channel sensing.

3) X-MAC: Contrary to the previous two protocols, X-MAC is primarily a link layer protocol. X-MAC aims to achieve better lifetimes by employing a shorter preamble and preamble sampling time when compared to protocols like S-MAC and B-MAC. X-MAC is an adaptive algorithm that dynamically adjusts the receiver duty cycles to optimize energy consumption per packet, latency, or both parameters. X-MAC has two proposed ideas to reduce energy consumption. First, embed addressing data inside the preamble, so that receivers which do not need to receive the packet can go back to sleep mode, saving power. The second idea is to use a strobed preamble; this allows a receiver node to interrupt the transmitter before an entire preamble duration, reducing energy losses on both transmitter and receiver side.

More modern MAC protocols, such as BOX-MAC have been introduced that use information in multiple layers to make more informed decisions about the state of the network, thereby, making more efficient use of the radio and reducing power consumption by up to 50% when comparing X-MAC with BOX-MAC [10], and up to 30% when being compared to B-MAC.

4) BOX-MAC: BOX-MAC was developed as an evolution of both B-MAC and X-MAC, while the earlier two protocols rely on a single layer for information to perform power savings, BOX-MACs 1 and 2 rely on information contained within both the physical and link layers to achieve the goals of LPL. Of the two versions of BOX-MAC, BOX-MAC-1 is a predominately physical layer protocol that incorporates link layer information, and BOX-MAC-2 is a packetized link layer protocol that incorporates physical layer information.

BOX-MAC-1 acts as an improved version of B-MAC, instead of B-MACs preamble, BOX-MAC-1 transmits a continual data packet. This allows nodes to save power by only staying awake for packets that are meant for them. BOX-MAC-2 improves upon X-MAC by first checking whether or not there is sufficient energy on the channel as opposed to waking up long enough to hear a complete packet. Because of this, BOX-MAC-2 reduces receive check lengths by a factor of 4 compared to X-MAC.

BOX-MAC-1 has been shown to be more efficient when network traffic is low and BOX-MAC-2 is better at high traffic applications. Because of this, and the base protocols they were derived from, WURs have been compared with B-MAC and BOX-MAC-1 in low traffic situations and with X-MAC and BOX-MAC-2 in high traffic situations.

B. Wake up radios

There are two types of implementation for wake up radios, namely an identity-based system and a range-based system. Range-based systems work by transmitting a wake-up tone which is then received by all nodes within range and triggers all of those nodes to wake up their processors. Identity-based systems work on the principle of a bit-sequence being received and then decoded and checked against a pre-set identity.

1) Range based systems: These systems are often charge pump based, and are realized using Schottky diodes [11] or MOSFETs [7]. Once sufficient activity is detected on a channel, the wakeup circuit will then trigger an interrupt on the sleeping micro-controller. The downside to this approach is that a correct wakeup signal is treated the same way as any other RF activity on that frequency, leading to an increase in false wakeups, triggering the main radio more often than necessary.

The attractive feature of these circuits is that they have very low power consumption and in some cases can be completely passive circuits [2], the caveat being that passive circuits have even less range than active receiver based circuits.

2) Identity based systems: Identity based systems are able to process information carried in the wakeup signal i.e. an address. This results in less false wakeups per mote as only motes that are actively being addressed will wake up the main radios to receive data. Data is clocked into a register and is compared against a pre-set value [4]. If the compared values are correlated, a wakeup signal is sent to the micro-controller

TABLE I: WUR SUMMARY

Radio	Active current draw	Sensitivity(dBm)	Frequency (Mhz)
[6]	6µA	-80	868
[9]	2.4µA	-71	868
[1]	1.37µA	-67	0.11 - 0.15
[12]	18800µA	-98	2400

and then the main radio is switched on to receive the data packet.

C. Advantages and disadvantages

Clearly, the reduced operational range of wake-up radios diminishes their suitability in networks that require large ranges between nodes while still maintaining a short latency interval. Additionally, adding in a wakeup receiver increases the complexity of hardware design on already constrained systems so careful consideration must be taken into account when designing such a system. The increased complexity and, therefore, the increased cost of the overall system may negate the yields gained from prolonged battery lifetimes.

The advantages of wake-up receivers include their much reduced operational power requirements (µA operating current versus mA for traditional radios). Also, as the wake up receiver is constantly receiving, the requirement to synchronise between sender and receiver is removed as it has become a purely asynchronous communications network.

III. Analytical Work

This paper aims to show that using WUR technology, energy savings can be made in compared against LPL techniques.

All calculations in this paper are based purely on the consumption of the radios as all other system components are assumed to be equal and that their energy usage will remain the same throughout all experiments, as a result of this, lifetimes presented in the results will be higher than those achieved in reality as the whole system will use more energy than is being calculated here.

For this paper, Chipcons CC2520 [12] radio has been selected to represent the main radio technology as it is widely used in WSN testbeds [11]. While many different possible WUR technologies can be used (shown in Table I), a device in the 110kHz ISM with a current consumption of 1.37 µA [1] to represent a WUR with a decent sensitivity. These radios are summarized in Table I. The lower sensitivity radios equate to an indoor range of approximately 30m [6], which should be sufficient to cover a typical office room.

Utilizing wake-up radios presents certain changes to the calculations [10] used for the time the radios perform various tasks; these changes are summarized in Table III.

For the analytical work, this paper assumes a standard time for transmission of valid packets of 4.1ms (802.15.4 payload transmission time) which remains equal for both LPL modes as well as WUR solutions. The reason for the added 0.5ms is that it takes this extra time to wake up the main radio from sleep to active mode. TCX in this case equals the number of milliseconds in a day as the radio is always listening.

These changes are reflected in Table III. Using the adjusted calculations from Table III, and a Schott Solar cell which is capable of generating up to 151.6 µW [15], a theoretical limit for number of valid wake up messages per hour using a WUR system was arrived at of 109 messages if using a single Schott Solar cell. This measure does not take into account sending messages back to a base station; further investigations will need to be carried out to determine the upper limit for communications in both directions.

Assuming that transmitting a response to a query would take approximately the same amount of power as receiving one packet, such a system would be able to achieve 55 asynchronous communications per hour. Using these equations from Table II and Table III, a graph was plotted to visualise average power consumed by each method for varying amounts of valid packets per hour, this is visualised in Figure 1.

IV. Experimental Setup

In order to validate the analytical calculations in III an experiment was devised to measure the power consumption of LPL and Wake up radios. The first step of the experiment was to measure power consumption on this platform in the following scenarios, the wireless platform consuming the minimum power possible to establish a baseline of power consumed by the MCU and radio in sleep mode.

Next, the state of the art in low power listening methods was measured for different values of receive check interval. The LPL techniques selected were the physical layer B-MAC, link layer X-MAC and the hybrid protocols BoX-MAC 1 and 2. No transmissions were carried out these measurements were

TABLE II: ORIGINAL ENERGY CALCULATIONS

Time spent on wake-up transmission deliveries	T_TX (box1, bmac)= D * T
	T_TX (box2, xmac) = D * (T / 2)
Time spent on incorrect radio packets	T_I (box1, box2, xmac)= I * 20ms
	T_I (bmac) = I * T
Time spent for valid radio packets	T_V (box1, bmac)= V * (T/2 + 4.1ms)
	T_V (box2, xmac) = V * 4.1ms
Time spent checking the channel.	T_CX (box1, bmac) = R * 0.78ms
	T_CX (box2) = R * 5.61ms
	T_CX (xmac) = R * 20ms
Time spent on idle power	TIDLE = Msec in day - (T_TX + T_I + T_C + T_V)

TABLE III: ADJUSTED CALCULATIONS FOR WUR

Value	Time spent per day
Time spent on wake-up transmission deliveries	T_TX = 0ms
Time spent on incorrect radio packets	T_I = I * 20.5ms
Time spent for valid radio packets	T_V = V * 4.9ms
Time spent checking the channel	T_CX = 86400ms
Time spent on idle power	T_IDLE = (86400ms - (T_TX + T_I + T_V))

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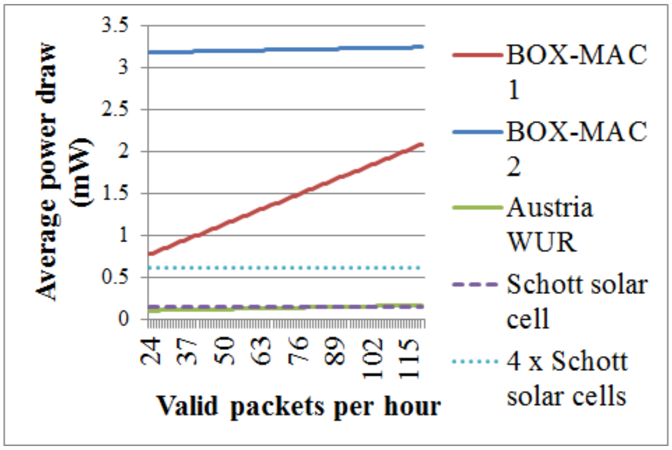

Fig. 1: Power draw calculations

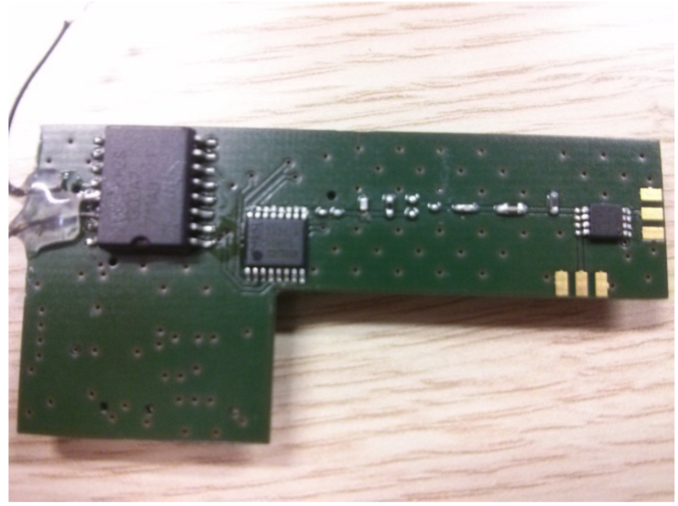

Fig. 3: Tyndall WUR expansion board

only used to get the baseline average power consumption of each LPL method.

For the hardware used in this setup, a wireless mote consisting of an MSP430F5437 microcontroller and a Texas Instruments CC2520 was chosen as the radio platform. The mote platform is shown in Figure 2. The mote is a credit card sized platform with expansion slots for additional peripheral devices (sensor layers, radios, actuators etc). The mote also has a number of jumper selectable options for power sources and power distribution allowing complete control of which sub components of the mote get powered up. For example the on-board FTDI chip can be enabled or disabled depending on the configuration required.

To take advantage of the modular nature of the platform, a daughter board was developed, pictured in Figure 3. This board has a 32 kHz crystal acting as an external clock source for an Austria AS3933 WUR. There is also a radio frequency passive network on the daughter board which is tuned for 2.4GHz signals.

The AS3933 WUR uses on off keying (OOK) modulation, while it is an identity based WUR it can also be setup as a ranged based WUR through register settings. The passive network performs a low pass filtering of the 2.4 GHz signal down to 125 KHz in a fashion similar to that used in [11], which is the frequency the WUR operates on.

To perform the power analysis, a DC Power Analyser from Agilent Technologies (N6705B) was used to provide power to the entire device via the red (positive) and blue (negative) wires seen in Figure 4. The entire setup is shown in Figure 5. 64k points of measurement over 4 seconds were taken using the scope view function and then exported into csv format. These individual points were then averaged to arrive at the figures displayed in Table IV.

V. RESULTS

Setting the supply voltage at 2.5V, measurements were taken for low power listening methods when no packets are

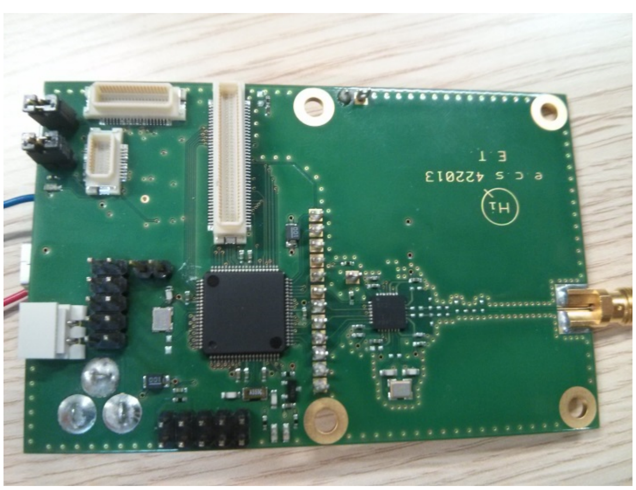

Fig. 2: Tyndall Mote

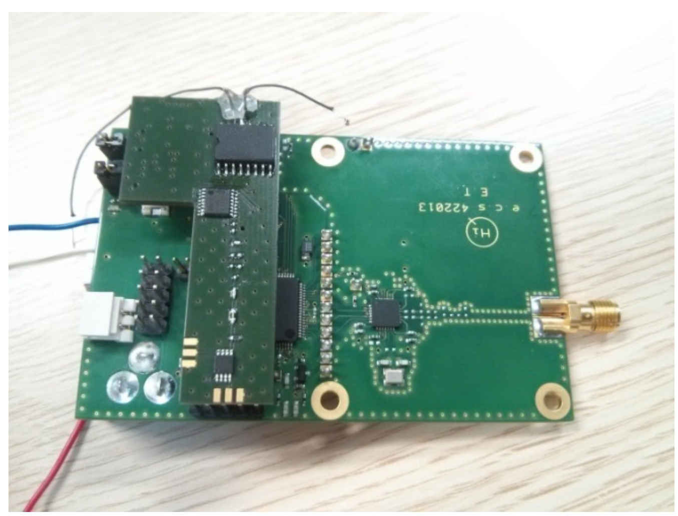

Fig. 4: Boards connected

TABLE IV: POWER MEASUREMENT RESULTS

Protocol	Receive check interval	Radio duty cycle (%)	Average power (μW)
All sleep mode	0	0	15.7
WUR	0	0	54.1
BMAC, Box-MAC1	50ms	1.52	1113.5
	500ms	0.152	128.95
	1s	0.076	72.5
	2s	0.038	45
Box-MAC2	50ms	11.22	6128
	500ms	1.122	631.53
	1s	0.561	326.4675
	2s	0.2805	176.75
XMAC	50ms	40	22022.75
	500ms	4	2138.49
	1s	2	1080
	2s	1	549.345

delivered to determine absolute minimum power expended for each method. The results are recorded below in Table IV.

The MCU is in low power mode whenever it is not communicating with the radio chip, and the CC2520 is in the lowest power mode (LPM2) when it is not in receiving mode to listen for packets. The addition of the WUR to the base system imposes an additional 40μW requirement for minimal operations.

This base level requirement of 55μW is easily attained using Schott Solar cells that can generate up to 151.6 μW each [15]. Also from Table IV, for a single solar cell, LPL methods are unable to achieve a low enough average power draw while maintaining a low latency.

Comparing the LPL methods, XMAC consumes the most power because of its relatively large on time for the radio when performing a receive check. BMAC and BOX-MAC1 consume equal amounts of power because the main radio is receiving for equal lengths of time. The length of time the radio is on and in receive mode is listed in Table II.

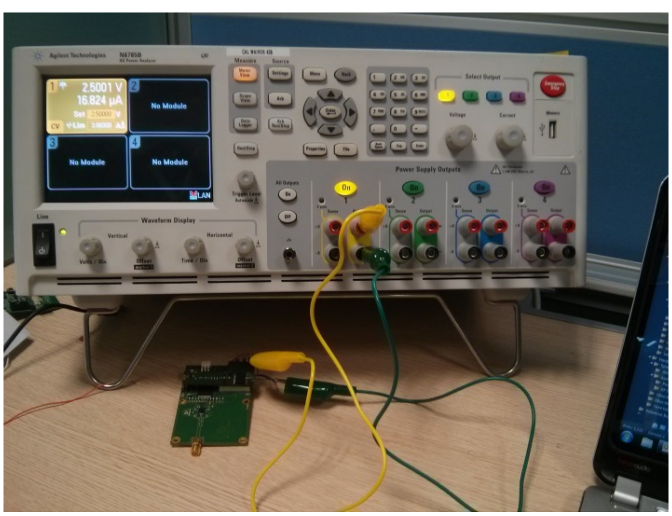

Fig. 5: Device under test

VI. Conclusion

From the analytical work done, it has been shown that WUR are much more suited to indoor battery-less solutions than LPL techniques. Furthermore, from the initial recorded measurements of power, the empirical data suggests that WURs offer a lower power consumption while still maintaining a lower latency over LPL methods. There are certain scenarios where WUR would not be suitable for a WSN, namely where a long range between motes is required while still maintaining a low latency in mote-to-mote communications, however, in situations where long range is not required but latency is not a crucial factor, WURs can still be employed to prolong the lifetime of motes in a WSN. Wake-up radios can reduce the energy usage of a system to a point where it would enable indoor, asynchronous communications powered by indoor based energy harvesting methods, which typically dont offer as much energy as outdoor solutions.

VII. Future Work

The first step in creating a battery-less bi-directional wireless sensor platform is to ensure the power consumption of the device is kept to an absolute minimum. Box-MAC1 when its receive check interval is set to 2s, achieves low power consumption (250uW). However, this figure still exceeds the power provided by a single solar cell making it unsuitable for an indoor EH solution that is based upon a single solar cell [15]. The authors propose to perform the following:

1) Integrate the mote platform (Figure 4) with Tyndalls in house energy harvesting platform [15], pictured in Figure 6.
2) Include a sensing layer on to the mote; employ asynchronous communications using the WUR.
3) Build large scale deployment of battery-less WSN platforms utilizing WUR technologies.
4) Using a large scale deployment, validate the usefulness of WUR in modern WSN deployments.

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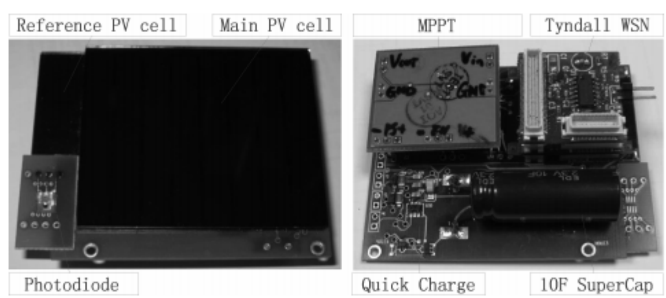

Fig. 6: Energy harvesting platform

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