Plug into a Plant: Using a Plant Microbial Fuel Cell and a Wake-Up Radio for an Energy Neutral Sensing System

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***Abstract*—As a step toward sustainable wireless sensing, we present a proof of concept system that uses a Plant Microbial Fuel Cells (PMFC) as a power source. To match the very low power production capabilities of the PMFC, we couple it with an ultra-low power wake-up receiver used as a trigger for sampling and transmission of the sensed value. We demonstrate that this combination, with a new, receiver initiated MAC-level communication protocol, results in a sustainable system for reasonable data rates, shown to be 30s in our laboratory setting. This work offers the first steps toward large-scale wireless sensor networks in applications where the sensors are surrounded by living plants that can provide a green and perpetual power supply.**

1. Introduction

Wireless sensor systems have witnessed extraordinary growth over the past decade, particularly for monitoring infrastructures, natural environments, habitats, logistics, and most significantly for security. In most cases, sensors are deployed in remote locations with limited access to a continuous power sources and yet require lifetimes from several months to a few years. As such, sensing devices are typically battery-powered.

To extend battery life, sensor nodes exploit low power consumption states such as standby or sleep, duty cycling between active and inactive modes to save power. Although the current drawn in the sleep mode is relatively low, over a long lifetime or with many nodes deployed, a large amount of energy is wasted. To quantify this, consider that for the popular Tmote node [1], the CC2420 radio module consumes 20 μA when powered down and the MSP430F1611 MCU consumes 2.0 μA in the sleep state. Over a day, this amounts to a baseline total of 5.718 J, while additional tasks such as sensing, computation and communication significantly increase this value.

Motivated by this analysis, we turn our attention to reducing node consumption with innovative low-power hardware technologies. Specifically, we propose an on-demand sensing system, where an extremely low power switch is continuously powered by a novel plant-based microbial fuel cell, PMFC. The switch contains an ultra low power wake-up receiver, which can be remotely triggered with a wireless signal. Receipt of the trigger causes a standard Tmote to be woken up to sense then transmit data.

A microbial fuel cell, MFC, converts the chemical energy of organic matter found in sediment into electricity by exploiting the metabolism of bacteria [2]. Therefore, PFMCs offer a promising power source for sustainable low power sensing applications in natural environments such as precision farming or greenhouse monitoring. Nevertheless, PFMCs are severely limited in the quantity of energy they can generate. Specifically, due to high internal resistance and low power output, PMFCs are not able to directly power electronic devices [3]. Therefore, in this work, an intermittent energy scheme in the form of a boost charger and a capacitor is utilized to harvest and to store the energy. The boost charger converts the low potential generated by PMFC to a higher one to charge the capacitor. The energy stored by the capacitor is then used to continuously supply the on-demand switching system.

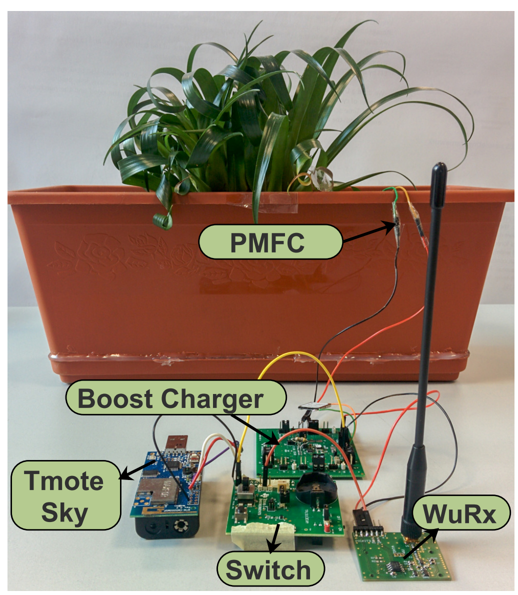

Figure 1: Laboratory setup of the plant microbial fuel cell powered sensing system showing different modules.

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The system is completed by a standard sensor node, a Tmote, which is completely off except when it is triggered externally by the always-on wake-up receiver component of the switch. The remote, plant-powered system is periodically queried by the sink node, which collects and stores the data. Once the data transmission is completed, the power is completely cut off from the sensor node while the switch with the wake-up receiver is kept in listening mode.

We assume the sink node is battery powered and works in a duty-cycle manner where, periodically waking up and sending signals to pull data from the sensing nodes. During periods of inactivity, the sink node is also put into a low power mode to save energy. The overview of the full lab setup is shown in Figure 1.

Following a description of the core technologies we rely on in Section 2, we offer two main contributions: (1) a system design that combines multiple, novel hardware and communication technologies to obtain a fully energy autonomous sensing system, described and modeled in Sections 3 to 5 and (2) a concrete in-lab evaluation of these technologies to validate the feasibility of our proposal in Section 6.

2. Background

This section offers background on the novel technologies and techniques used throughout this paper to achieve a self-sustained and maintenance-free on-demand sensing system for autonomous long-term monitoring. We first discuss energy harvesting using plant microbial fuel cells followed by ultra low power wake-up receivers.

2.1. Plant Microbial Fuel Cell

Microbial fuel cells are bioreactors that exploit a property of particular bacteria, namely producing electrons as a result of their own natural metabolism. These microbes are found in the major part of the soils and sediments on the planet. To extract power, typically two electrodes made of inert material such as graphite are used. The anode is buried under the sediment while the cathode is placed on top where oxygen is present. Electricity is generated by the oxidation of sediment organics as a byproduct of microbial metabolism. The typical continuous power output that can be exploited with a carefully designed harvesting circuit is approximately 50 to 100 μW at 0.3-0.6V level.

We have shown in previous studies [4] that the addition of flora/plant inside the MFC ecosystem invigorates the performance of the bacteria, boosting the power generation from the MFC and incrementing the output voltage [2]. Further, the plant extends the lifetime of the bacteria by providing more nutrients to the soil. Researchers have also shown that harvesting electricity does not affect the plant-growth. The overall result can fit in a standard potted plant requiring only the typical care of occasionally watering to keep the soil moist and the plant alive, which in turn generates a small amount of electricity that can be exploited by the system.

Finally, various factors have been reported to have a major impact on the performance of MFCs [5]. Principally, the ambient temperature greatly affects the microbial activity. Further, dissolved oxygen at the anode impedes power output, and the distance between the electrodes affects the internal resistance of MFCs. Poorly managing these factors can prevent the output power from reaching the optimal value.

2.2. Wake-up Radios

Recent developments in CMOS power dissipation have resulted in the new paradigm for communication technology of wake-up radios (WuR) [6]. WuR technology is a novel, energy efficient hardware solution that offers listening power consumption orders of magnitude lower than that of traditional radios utilized in WSNs. For instance, the wake-up receiver (WuRX) adopted in this work requires 0.56 μA of current in listening mode while CC2420 radio module requires 18.8 mA.

Recently, numerous WuRX hardware solutions have been developed and tested [7], [8], each optimizing different parameters such as operating power, receiver sensitivity, communication range, frequency, and latency. A vast majority of these solutions are RF based, but alternatives include acoustic and optical. As these devices are low-power designs, the traditional radio and WuRXs are orthogonal to each other in terms of data rate and receiver sensitivity. This limits the choice of modulation techniques, receiver complexity, and the achievable communication range of WuRXs.

As a consequence of the ultra low power consumption, WuRXs are typically used in an always-on manner, but are only able to receive a simple, wake-up signal, hence motivating their name. Some WuRXs also provide computational capabilities at the cost of a few additional microwatts, allowing them to decode data embedded in the signal. As a result, it is possible to perform address matching or configure system parameters without activating the other sub-systems of the sensing node.

Recent studies have shown the potential of WuRXs for asynchronous communication in application scenarios [9], [10], [11]. These case studies have shown that, in comparison to duty cycling protocols, WuRXs dramatically reduce the power consumption footprint of wireless, battery powered networks for applications with low data traffic, offering better reliability and lower data latency.

3. System Architecture

Figure 2 offers a high-level overview of our proposed plant-based sensing node system composed of the energy harvester, the on-demand switch, and the sensor node. Notably, the only power source is the plant-based harvester. The system is completed by a sink node composed of a battery powered Tmote. This section offers a high-level description of the primary components and how we use them in this case study.

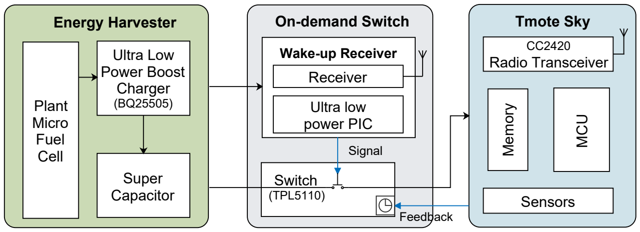


Figure 2: Overall architecture of the wake-up receiver triggered on-demand sensing unit. When a trigger is received, the switch closes to connect the sensing and transmitting node to the PMFC-based energy harvested power supply. Black lines indicate the power supply while blue indicates trigger signaling.

3.1. Energy Harvester

The energy harvester is the core of our system as it is responsible for power generation and distribution to the node. It is composed of three sub-blocks:

PMFC. The PMFC provides the power source, making the remote node design very challenging because of the low power it delivers. The prototype we used is made up of pot filled with soil from the university courtyard, a standard houseplant able to survive in a very moist environment, and two graphite fiber felt electrodes. After several days of setup time in which the bacteria colony starts growing, the system is able to produce an average output power of 70 μW.

Boost Charger. Due to the low output voltage of the PMFC, the energy harvesting module is interfaced with a TI BQ25505 boost charger that shifts the low input voltage to a higher output one to charge the capacitor. This particular IC is chosen as it requires a ultra-low quiescent current of 5 nA, compliant to the PMFC power production, and also embeds a maximum power point tracking (MPPT) that allows maximizing the power extracted from the harvesting source. Through experimental measurements, the efficiency of the boost charger is found to be 90 %.

Super capacitor. The output of the boost charger is then used to charge a single 22 mF super capacitor that is the main storage bank in our case. The intermittent energy harvesting scheme that we adopted uses cyclic charging and discharging of the capacitor to store the energy generated by the PMFC. At full charge, the capacitor is able to provide 33 mJ, enough to power the entire system for a short period. The size of the capacitor in our design can be tuned, depending on the characteristics of the power source and energy requirements of the system.

3.2. On-demand Switch

The energy harvester and the sensor node are separated by the on-demand switching system that is the key component for connecting and disconnecting power to the node. As power consumption of the Tmote Sky is typically hundreds of micro-watts, much more than the PMFC can continuously supply, it is essential to incorporate a cutoff switch so that enough energy can be accumulated by the capacitor to power the sensor node only when required. The switching system uses two main components to effectively achieve on-demand sensing. An always-on wake-up receiver detects the trigger from the sink node. This then controls a switch to bridge the power from the energy harvester to the node.

Wake-up Receiver. The WuRX solution that we adopted is a custom designed ultra low-power module, representative of most WuRXs found in the literature. The WuRX module operates in the ISM 868 MHz band and has a high receiver sensitivity of -55 dBm with a maximum communication range of 50 m. It also features an ultra-low power MCU that is used for decoding an address embedded in the RF carrier for selective triggering. The overall power consumption has been experimentally measured at 1.68 μW in standby mode when listening for the signal, and 1020 μW when it is actively receiving and decoding the preamble or address. Wake-up triggering time was measured as 16 ms for the 16-bit address mode.

Nano-power Switch. As mentioned in Section 1, when there are no sensing tasks to be performed, we turn the sensor node completely off as the energy harvester cannot provide enough power to keep the node in sleep-mode. As shown in Figure 2, the TPL5110 switch connects the power supply to the Tmote when it receives the signal from the wake-up receiver. The cycle repeats every time the on-demand switch is triggered. The TPL5110 chip incorporates a low power timer with an integrated MOSFET driver for switching and consumes only 35 nA. It also supports a number of modes and can be used as a stand-alone timer for systems that have to wake-up periodically.

3.3. Sensor Node

After the switch is triggered, the Tmote is powered ON, performs the sensing and communication then raises feedback to the TPL5110 IC through GPIO (HIGH) indicating that it is time to cut power. We adopted the Tmote Sky as the main remote sensing node as it is a popular platform used by the sensor network community for research purposes. Moreover, it is also supported by ContikiOS and COOJA simulator. The platform is designed around the TI MSP430F1611 MCU with a low-power CC2420 radio transceiver offering a 250 $kbps$ data rate and operating in the 2.4 GHz band. It also includes three onboard sensors: humidity, temperature, and light. The Tmote also offers various low power modes. The average power consumption is approximately 58 mW when transmitting, 65 mW when receiving, and only 163 μW in idle and 15 μW in standby mode. In our setup, the Tmote runs the Contiki Operating System that is used to control the radio transceiver via a custom MAC protocol detailed in Section 5.

The choice of the Tmote provided a rapid prototype to evaluate the effectiveness of the MAC scheme. In the future, we will consider alternate, ultra-low power MCUs, such as ARMCortex-M4 processors [12], [13], and radios that will facilitate the design of an energy neutral wireless sensing system powered by PMFC.

TABLE 1: Laboratory power and current measurement of the different components in various states. Idle reflects listening to the channel, but not actively receiving.

Component	Current Consumption
Tmote (MCU on, CC2420 TX mode)	19.5 mA
Tmote (MCU on, CC2420 RX mode)	21.8 mA
Tmote in deep sleep mode	43 μA
WuRX in idle state	0.56 μA
WuRX (Receiving + address decoding)	340 μA
WuTX (Transmitting)	10 mA
Component	**Energy Budget**
Sensor Node + Switch (Active)	3.6 mJ
WuRx idle + DC-DC Boost + Switch (Baseline)	1.8 μW
Other Parameters	
CC2420 bit rate	250 kbps
WuR bit rate	1 kbps
Application Payload	6 B
WuR addressed packet size	2 B

4. Energy Requirements and Delivery

To ensure perpetual operation, the energy required by the sensor nodes for processing, sensing, and communicating ΔE_{node} must be balanced with the energy harvested from the plant micro fuel cell ΔE_c. If $\Delta E_c < \Delta E_{node}$, the device will run out of power and fail. Achieving the proper balance requires analysis of the requirements of various hardware components as well as energy efficient protocols that can operate within a strict energy budget.

This section presents a model for estimating the energy production or requirements of various system components including:

1) the energy required by the sensor node E_{node},
2) the energy delivered by the PMFC in continuous operation E_{mfc}, and
3) the energy that can be stored in the capacitor E_c as a function of time.

4.1. Baseline Power Consumption

In our laboratory, we measured the average sleep power of the Tmote at 130 μW, a value higher than what the PMFC can continuously supply. Therefore, in our proposed system, the Tmote is completely shut down, except when an external trigger arrives to indicate a sensor should be probed and its value sent. While this technique saves energy, not all components can be turned off, specifically the boost charger, wake-up receiver and the switch must remain active, together consuming a non-negligible amount of power: 1.8 μW (600 nA) in idle mode. This baseline power consumption is illustrated in Figure 3a and reported in Table 1 as the baseline.

4.2. Active State Power Consumption

When the sensor system is triggered, a number of actions take place: reception of the trigger, powering up of the sensor node, sensing, and transmission of the sensed value. Table 1 reports these individual costs along with other, common functionality of the Tmote, e.g., CC2420 RX, even though we do not exploit them in this paper. The total energy consumption of the remote node is the sum of the energy consumption of its individual hardware components i, plus the costs of the on-demand switch, processor, radio transceiver, and the sensors. The total energy $E_{node}(t)$ required by the node is then computed as the product of the power and the time taken to carry out each task:

$$E_{node}(t) = \sum_i P_i(t) \cdot T = \sum_i V_i(t) \cdot I_i(t) \cdot T \qquad (1)$$

Each of these tasks is labeled in Figure 3b. In region A, the trigger signal is received over the WuRX and the PIC micro-controller is activated for decoding and address matching. During this process the current consumption of the WuRX increases from 1.68 μW to 1.02 mW for a period of 16 ms. If the address is a match, the switch is closed to turn on the Tmote Sky (60 mW spike). The Tmote Sky turns ON and enters into sleep mode (with a current draw of 43 μA) and then switches to an active mode for at most 640 ms (region *B*). This period is required to boot up and stabilize the crystal oscillator. Finally, region *C* shows the measured power for sensing and communication. The Tmote Sky turns on the on-board temperature sensor and samples the value. It then turns on the CC2420 radio to send this sensor reading to the sink node before locally signaling the transmission done to the switch. The whole process from triggering to transmission on average takes 680 ms. Hence, the maximum energy demand measured during the active mode is E_{node} = 3.6 mJ.

4.3. Energy Delivered by the PMFCs

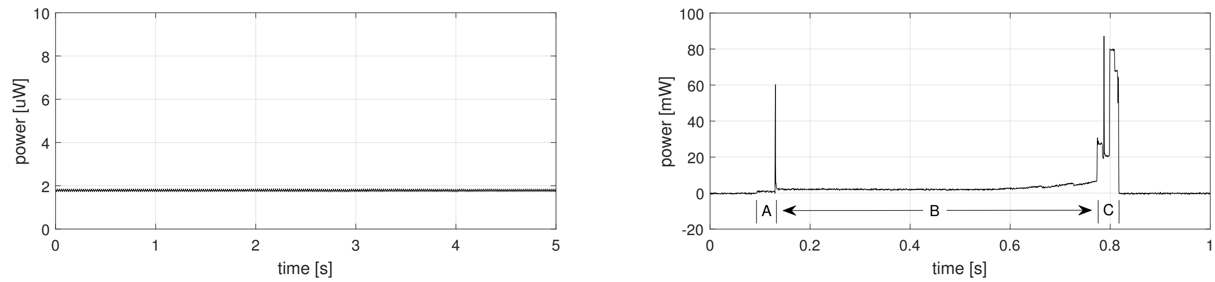
Over several months of monitoring in an indoor environment, we measured the average output power that can be extracted from the designed PMFC (shown in Figure 1) is E_{mfc} = 70 μW. This average value can grow up to 300 μW peak for short periods of time if the plant is healthy, usually followed by a recovery period needed to restore the normal “idle” operating condition. This way of operation is well exploited by our power management system that drains power only when the wake-up receiver is addressed.

4.4. Energy Stored by the Capacitor

To supply continuous power to the on-demand switch and peak power to the sensor node we exploit a $22mF$ capacitor, which, when fully charged, supports 3.36 $volts$. The energy E_c stored (accumulated) in the capacitor when it was charged from $V_d = 2.87V$ to $V_c = 3.36V$ is estimated as:

$$E_c = \frac{1}{2}C(V_c^2 - V_d^2) \qquad (2)$$

where C is the capacitance and the V is the supplied voltage from the boost charger. At full charge, the capacitor provides



(a) Baseline power consumption. (b) Active state power consumption for the whole system.

Figure 3: Power consumption measurement of the remote sensor node with radio-trigger capability. In (a) the baseline consumption including the wake-up receiver in idle is approximately 1.8 μW, while in (b) the active power of the whole remote node when triggered (i.e. from trigger to transmission) is 3.6 mJ. Note the axes have different ranges and units.

E_c= 33 mJ. This stored energy is more than enough to supply the burst energy required for the measurements and transmit operations, quantified as 3.6 mJ. Further, we note that the size and number of capacitors can be modified depending on the system's power requirements.

5. Energy Efficient Communication for Sustainable Sensing

We now move on to the basic operation of the communication, describing our Wake-up radio based Receiver-Initiated MAC (WRI-MAC) for data collection in a star network. We begin with an introduction to the basic idea followed by presentation of the communication scheme between nodes.

In Receiver-Initiated systems (RI-MAC), the burden of starting a communication event falls to the receiver, specifically with a node, often the sink, announcing its readiness to receive data. After this announcement, it switches to receive (RX) mode and monitors the wireless channel for any incoming packets. Our choice to adopt a receiver-initiated MAC was motivated by two facts. First, RI-MAC protocols require no network synchronization among sensor nodes thus offering pure asynchronous communication. Second, collisions among senders are eliminated as the receiving

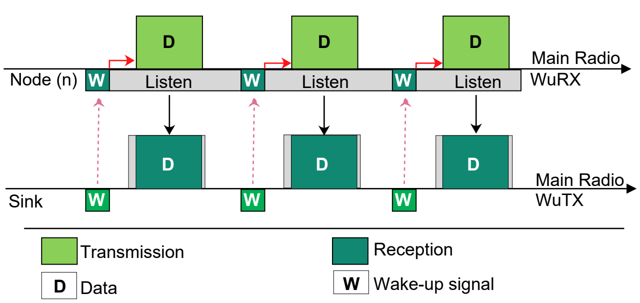


Figure 4: WRI-MAC in unicast mode using address-based wake-up beacons. A single, separate wake-up beacon (W) is sent to initiate communication with each respective transmitter.

node is in charge of pulling data from the individual nodes when required.

WRI-MAC, proposed in this work, assumes that each remote plant-powered node is equipped with a Tmote Sky and a wake-up receiver while the sink node is equipped with a Tmote Sky and a wake-up transmitter. WRI-MAC operates in both unicast and broadcast modes and has been implemented for ContikiOS.

Unicast Communication. In the unicast communication paradigm, as shown in Figure 4, the base station first transmits a wake-up beacon (trigger signal) through its wake-up transmitter containing the specific node address that it wants to query. The sink then turns on its main data transceiver and samples the channel for 15.6 ms to receive an incoming packet. On average, the packet transmission takes no more than 8 ms, however, we have over provisioned to improve synchronization between source and sink and to reduce packet losses. After reception, the node either repeats the trigger process with other remote sensing nodes or goes back to sleep until the next samples should be collected, a time we refer to as the trigger-interval.

On the side of the remote sensing node, the WuRX is always in the listening state, waiting for a wake-up beacon from the sink. The receipt of the wake-up beacon containing the targeted node's address generates a HIGH pulse on the GPIO of the microcontroller to trigger the power switch, activating the Tmote. The remote node then sends the data packet to the sink using the CC2420 transceiver on the Tmote. As the power available at the remote sensing node is limited by what is produced by the plant and stored in the capacitor, we avoid exchanging acknowledgements (ACKs) from the sink to the sensor nodes.

Unlike traditional receiver-initiated protocols, our proposed MAC not only eliminates idle listening at the receiving end but also the continuous transmission required at the senders.

Broadcast Communication. As an alternative, the initiation trigger can be broadcast, with the intent to wake-up *all* nodes in range. Broadcast based wake-up can reduce data latency w.r.t to addressed based systems since the wake-up receiver does not need to decode the wake-up packet. As such, it can trigger its main node more quickly after receiving the preamble.

Figure 5 illustrates our proposal for a broadcast-based WRI-MAC's broadcast mechanism. As shown, the receipt of a broadcast address, set to 11111111, causes the WuRX to disable address decoding mechanism upon detecting ones in the first 2 bits. This beacon provides loose synchronization among the remote sensing nodes, and all transmit at a different, pre-defined interval from trigger reception. After sending the trigger the base station enters a receiving window within which it accepts all incoming data via its main transceiver.

Using the single beacon saves energy at the sink side as multiple beacon transmissions are expensive. However, the energy saved is compensated by keeping the main radio on for a longer period. Further, this energy is expected to increase with an increase in the number of sensing nodes. Nevertheless, savings is also expected at the remote plant-powered nodes as the trigger need not be decoded, saving approximately 1 mW for 16 ms of decoding time. Similar to the unicast mode, no ACK frames are exchanged between sender and receiver.

Channel Configuration. As a final note, our WuR and main transceiver use different channels, eliminating the possibility of collisions between the wake-up beacons and the data packets.

6. Experimental Setup and Evaluation

In this section we present a proof of concept, controlled laboratory experiment composed of a sink and a single, remote plant-powered sensing node. We have used data collected from several weeks of monitoring the PMFC and we show multiple data collection experiments for system evaluation. To demonstrate system scalability, we turn to simulation, presenting results for multiple sensing nodes.

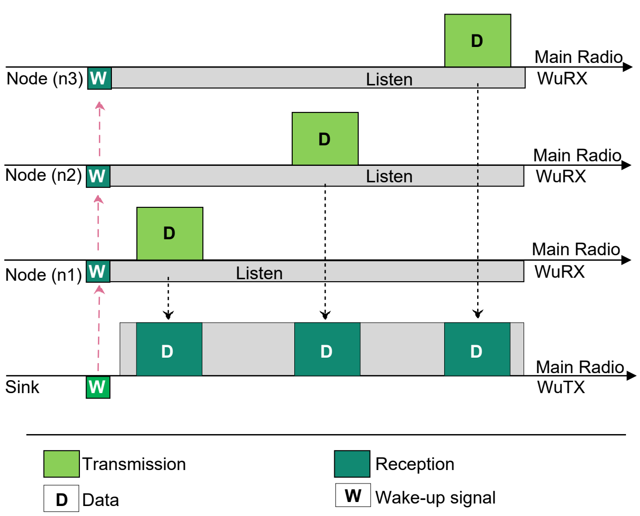


Figure 5: WRI-MAC in broadcast mode: a single broadcast wake-up beacon (W) is sent to acquire data from all the network nodes.

6.1. Output Power Characterization of PMFC

Our earlier studies [14] revealed that the best way to exploit the energy from a PMFC is in a bursty fashion, draining a maximum of 300 μW for short periods and then letting the cell to recover until it reaches the open circuit voltage.

To characterize and validate the amount of power that can be extracted from the PMFC, we conducted two separate laboratory experiments. In the first, the remote node is triggered, then the plant is given ample time to recover back to the open-circuit voltage of $0.36V$. The second represents a stress test to identify the maximum trigger rate that can be sustained with our setup.

The PMFC we used, shown in Figure 1, was monitored over a period of six months to observe the correlation between the microbial fuel cell and the plant. Data was collected with a National Instruments DAQ, while the power traces are obtained with an oscilloscope equipped with a custom amplifier to measure the power generated by the PMFC. A Keithley SourceMeter SMU2450 was also used to measure the actual power consumption of the sensing node.

Single-sample test: Figure 6 captures the instantaneous behavior of both the PMFC and the capacitor during the test, namely a single sample.

During a measurement interval of $100s$, the sensing node connected to the PMFC is triggered at $t = 2.5s$, shown by the voltage drop at this time. As soon as the switch is closed the capacitor begins to discharge as the stored energy is supplied to the node. At $t = 3.2s$ the sampling and transmitting task ends and the capacitor voltage begins to recover thanks to the energy harvester that returns to the charging mode resulting in the voltage drop across the PMFC until the capacitor is fully charged at $t = 38s$. There are also periodic dips in the PMFC voltage after the initial charging time, e.g., between 40 to $50s$. This is due to the capacitor discharging to supply the power to the on-demand switch. To restore this consumed energy, the charger kicks in until the capacitor is fully charged. After this, the PMFC stabilizes again.

It takes around $35s$ for the $22mF$ capacitor to be fully charged by the PMFC, indicating the maximum trigger interval that we can achieve. As we can see, once the capacitor reaches $3.36V$, the PMFC starts to recover until it stabilizes at $t = 90s$. We note that the size of the capacitor will affect the charging and the discharging time and the amount of data that can be collected. While larger capacitors may be used for powering the node for a longer period, they will also take longer to charge.

Stress Test: To evaluate the system under stress, we performed a test with a sampling interval shorter than the minimum, $35s$ interval identified in the previous section. Our objective was to understand how the plant responds in

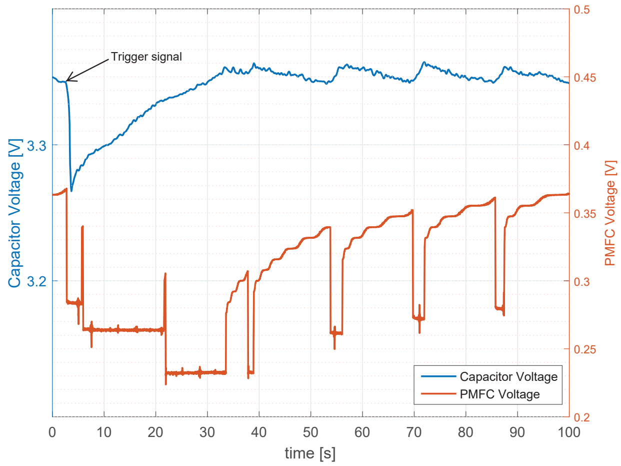


Figure 6: Instantaneous voltage profile of the PMFC (lower trace) and the buffer capacitor (upper trace). At the beginning the remote node is triggered and the PMFC is left to recover towards an open circuit voltage.

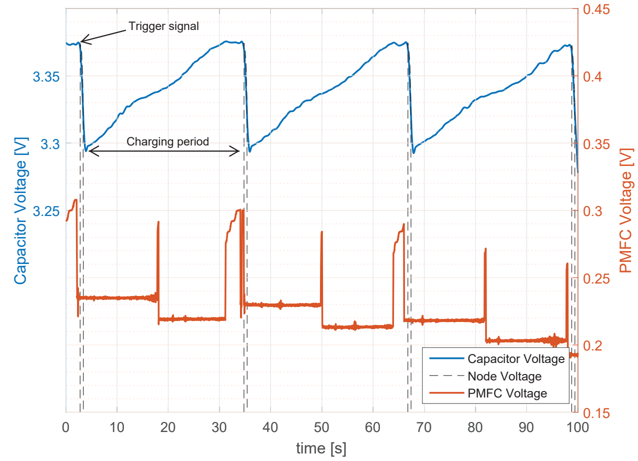


Figure 7: Voltage profile of the PMFC (red) and the buffer capacitor (blue) during stress test. The activation of the node is also highlighted by a dashed black line every time it was triggered.

this stressful condition. We used a triggering interval of $30s$ as shown in Figure 7. The capacitor and PMFC voltage were monitored over this period.

As shown, this triggering interval is sufficient to fully restore the capacitor voltage, however, it is not enough for the PMFC to fully recover and reach the open circuit voltage. Essentially, these stress conditions do not allow the flora and bacteria in the soil to recover.

6.2. Observations

Based on our experiments, we offer a few observations, first on reliability, then on system design.

To test system reliability, we sent 20 trigger signals with a trigger interval of 2 minutes and successfully received all 20 at the wake-up receiver side. Further, all samples were correctly received at the sink. In our setup, the distance between the remote plant powered node and the sink node was approximately 5 meters, therefore these perfect results were expected. Nevertheless, the reliability of the system with longer distances, e.g., closer to the $50m$ maximum range of our WuRX should be explored.

While performing our experiments, we did experience minor interference from nearby devices operating in the same frequency band causing false wake-ups. This caused sudden peaks in power consumption due to the PIC micro-controller on the wake-up receiver waking up to decode the RF signal. This potentially jeopardizes the stability of the PMFC, as it requires additional time to recover to the steady state.

Regarding system design, we note that our current system *is* able to support a reasonable data rate, as long as the sensing node is kept completely off in between samples. The PMFC provides sufficient power to constantly sustain the on-demand switch containing the ultra-low power wake-up receiver. Therefore, there is no need to consider alternative designs to further reduce the consumption of the switch, e.g., duty cycling the wake-up receiver.

Nevertheless, our design reboots the Tmote node to the same state in each interval, without requiring any state to be maintained across iterations. This is possible with our simple, star topology as no routing information is required, but more sophisticated topologies or systems may require additional energy storage capacity.

We evaluated only a single capacitor size, however, this can be modified according to the application scenario. For applications that require a higher data rate, multiple, smaller capacitors with shorter charging times can be considered. A larger capacitor may also be preferred to allow the node to be powered for longer, e.g., to receive an acknowledgment and possibly retransmit in the case of loss. Nevertheless, this impacts the time required to charge the capacitors, hence, requiring longer trigger delays.

Further, we recognize that environmental conditions also affect the behavior of the microbial fuel cells. A PMFC in an outdoor environment may generate more energy than the one we exploited, thus accelerating the charging time. There is also the possibility to connect multiple PMFCs in parallel to boost energy production [15].

6.3. Scalability

Our laboratory setting is limited by the available hardware, therefore, we turn to the WaCo-COOJA [11] simulation environment[1] to test the scalability of the system, specifically to estimate the power demand and the latency of networks with more than one remote node.

The distance between the sink and the remote nodes was fixed at $40m$. Unit Disk Graph Medium (UDGM) with

1. The source code of WaCo is available at https://github.com/waco-sim

TABLE 2: Scalability analysis using different MAC operation modes. The table shows the power consumption and latency w.r.t network size.

Mode	No. of Remote Nodes	Sink (mW)	Remote (mW)	Average Latency (ms)
Unicast	1	64	33	685
	3	195	33	685
	5	325	33	685
Broadcast	1	64	32	685
	3	97	32	780
	5	105	32	850

constant loss is used for the channel model due to its simplicity where nodes communicate and interfere in fixed-radius circles. The wake-up radio transmission is also fixed to $50m$ with a success ratio of 100%. The WuR signals are sent at 1 kbps and can contain 2B of address data. To test in a conservative setting based on our observations during the laboratory experiments, the trigger interval per node is set to 2 minutes. The energy consumption for the Tmote is obtained using Contiki's Powertrace and Energest power profiler. Results for 30 minute runs are reported in Table 2.

In all cases, we report the total consumption at the sink to receive the data from all remote nodes. For latency we report the time at the sink between the beginning of the transmission of the wake-up trigger and the termination of the receipt of the data. For unicast, this corresponds to the time between the transmission of the wake up receiver directed to a specific node and receipt of data from this node. Instead, in broadcast, as only a single trigger is sent, we start a timer at the sink when the trigger is sent and stop it when *all* data is received. For 3 nodes, the timer is stopped after receipt of the third sensor data packet.

In unicast mode, the power consumption at the sink linearly increases w.r.t the number of remote nodes. This is expected as the sink must send trigger signals to each node, round robin, to collect data. For each remote node, the average consumption remains constant at $33mW$. Latency also remains constant, as the probe to each node remains the same.

In the broadcast mode, consumption at the sink is significantly less for 3 and 5 nodes w.r.t. unicast. This is a combination of the fact that the sink transmits only a single trigger and a tuning of the timing at the remote nodes to minimize the idle listening time at the sink. On the other hand, we see the latency increasing. However, it should be noted that this latency reflects the time to receive all data, rather than the single readings, as in the unicast case.

7. Conclusion

As a step toward sustainable WSNs, we presented a novel system that combines the unique power source of a Plant-Microbial Fuel-Cell to produce the electrical power to sustain a standard Tmote node coupled with a wake-up receiver. By providing a novel receiver-initiated MAC protocol that exploits both the wake-up receiver as well as the main, CC2420 radio on the Tmote, we concretely demonstrate in the laboratory that a $30s$ sampling rate can be sustained for a single remote node, in a star topology. Future work is required to experimentally establish scalability and the capabilities of the system outside the laboratory.

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