Harvesting a Clock from a GSM Signal for the Wake-Up of a Wireless Sensor Network

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***Abstract*—This paper presents a low-power technique for harvesting a clock from the Global System for Mobile Communications (GSM) cellular network for the purpose of waking up and synchronizing nodes in a wireless sensor network. The 21-Hz clock is embedded within the broadcast channel of every GSM cell worldwide, making it a pervasive synchronization source. A low-power receiver architecture is presented to harvest the signal. Based on simulation results, the architecture can extract the clock with an error probability of less than 10^{-4}. Finally, a discrete prototype was built to verify the functionality of the receiver architecture.**

I. Introduction

The goal of wireless sensor networks (WSNs) is straightforward—to better sense our environment. They provide an alternative to wired networks, which can be costly, impractical, or obtrusive in many situations. As a result, there is significant interest in wireless sensor networks for a variety of applications including: environmental, biomedical, and industrial applications [1].

The realization of this goal, however, is significantly more challenging. To function effectively, wireless sensor nodes require significant communication, processing, and sensing elements, and for many applications, long-term deployments and small unit volumes are necessary to make them both cost effective and unobtrusive. The simultaneous desire for long lifetimes, small volumes, and portability puts significant strain on the battery. Energy conservation in the electronics has been one approach to reduce this burden.

In this work, we are proposing a wake-up radio architecture to harvest a clock from the broadcast channel in the Global System of Mobile Communications (GSM) network that can be used to wake-up nodes in a wireless sensor network (Fig. 1). The motivation for wake-up radios is discussed in Section II as an approach to synchronize a network in order to duty-cycle the high-power communication radio and conserve energy. In Section III, the concept of clock harvesting is introduced, and a viable synchronization signal embedded within the GSM standard is identified. In Section IV, the receiver architecture to harvest this signal is presented, followed by simulations to determine the probability of a synchronization error in Section V. Finally, measured results from a discrete prototype are presented in Section VI that demonstrate a clock signal being harvested from a GSM cell.

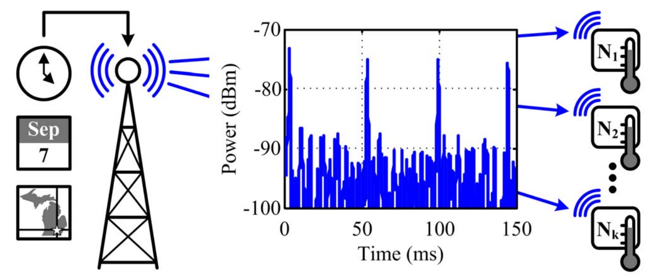

Figure 1. A wireless sensor network harvesting a clock signal for node wake-up. The plot shows a measured clock signal from the broadcast channel within the GSM standard versus time.

II. Motivation

A. Motivation for a Wake-Up Radio

To achieve long wireless sensor node lifetimes, energy usage in the electronics must be minimized. The communication radio typically consumes more power than any other component in a sensor node—e.g. a low-power radio may consume 1000x more power than a low-power processor [2][3]. Continuous wireless communication is therefore impractical for an energy-constrained node. As a result, the radio must be heavily duty-cycled, spending most of its time in the off-state. Duty-cycling, however, makes synchronized communication among nodes in the network challenging while still minimizing energy usage.

One approach to synchronization is to use a custom beacon signal to wake-up dormant sensor nodes and initiate wireless communication [4]. This requires a wake-up radio on the node to monitor the channel for the beacon signal. While this increases the complexity of the node, wake-up radios have been demonstrated that consume 52 μW, which is significantly less than the power consumed by the communication radio [5]. To utilize this synchronization technique, the wake-up signal must be generated *within the sensor network*, requiring additional power for its transmission. With the pervasiveness of today's wireless standards, however, it is conceivable for the wake-up radio instead to detect *an existing signal*, simultaneously eliminating the need to generate the beacon and conserving total energy in the network. Using an existing signal, however, will limit design flexibility in the wireless sensor network that could be

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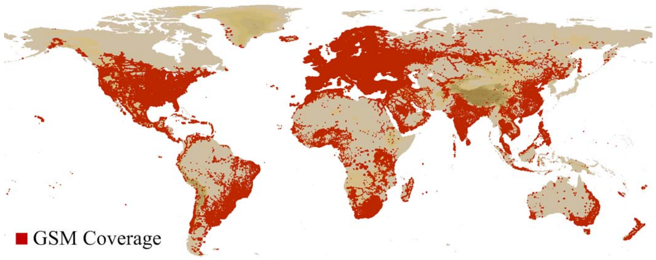

Figure 2. The 2009 Global System for Mobile Communications (GSM) worldwide coverage map, excluding 3GSM coverage [7].

used to better integrate the wake-up radio with the rest of the system.

B. *Motivation for GSM-Based Synchronization*

To realize low-power synchronization with a wake-up radio from an existing wireless standard, the beacon signal should satisfy several basic criteria. First, the signal should be pervasive so that a networked node placed anywhere on the globe can receive it. Second, the signal should be high-power to reduce the gain requirements in the wake-up radio along with the power consumption. Third, the beacon should have some component that repeats with low frequency that can be easily harvested as a wake-up signal. Finally, the synchronization signal should be simple to demodulate in order to simplify the wake-up radio receiver and minimize power consumption.

Of the existing wireless standards, GSM is particularly well-suited to provide the synchronization source. It has extensive worldwide coverage (Fig. 2), and within the GSM standard, a broadcast channel exists in every cell to synchronize mobile devices and provide other services. If a wireless sensor network were deployed within a cell, such that every node could receive the same GSM broadcast signal, then each wake-up radio would harvest the same clock, with mismatch only from differences in propagation delay. For a sensor network with a 100 m diameter, this mismatch error would be less than 1 μs. Furthermore, the harvested clock would have the accuracy of the GSM cell reference oscillator.

III. The GSM Broadcast Channel

GSM is a worldwide standard for wireless telephony and data communication. The standard exists in four major frequency bands worldwide with physical carrier channels of 200 kHz. The basic control services, such as frequency correction (FCCH) and broadcast control (BCCH), are provided together on a single radio frequency channel called the BCCH carrier [6]. Because these services are fundamental to network management, the BCCH carrier exists on every GSM cell worldwide, including newer GPRS- and EDGE-enabled cells. Thus, this signal is a good target for the wake-up of a wireless sensor network.

GSM is modulated using Gaussian minimum shift keying (GMSK) as well as several other modulation schemes with pseudo-GMSK spectrums. Signals are divided into multiframes, which repeat approximately every 235 ms (Fig. 3). During each multiframe on the BCCH carrier, a frequency correction signal is transmitted in five periodic bursts, called frequency correction bursts (FBs). During a FB a pure sinusoidal tone is broadcast by the GSM base station. This tone burst lasts for roughly 550 μs at an offset frequency of 67.7 kHz above the center frequency of the BCCH carrier. The rest of the time the BCCH carrier transmits data over a broader spectrum. Therefore, during a FB a peak in the power spectral density (PSD) of the BCCH carrier can be observed at the FB offset frequency (Fig. 4). This FB repeats continuously at a repetition rate of 21 Hz. By filtering around the FB offset frequency, a signal will be observed that looks like an amplitude modulated tone, repeating at 21 Hz. Since an amplitude modulated signal can be detected with a relatively simple demodulation technique, this signal is well-suited for low-power synchronization.

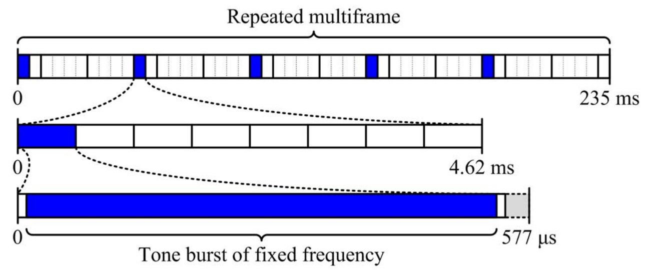

Figure 3. The organization of the broadcast control channel carrier, which consists of repeated multiframes with a tone burst generated at a fixed frequency during five of the timeslots.

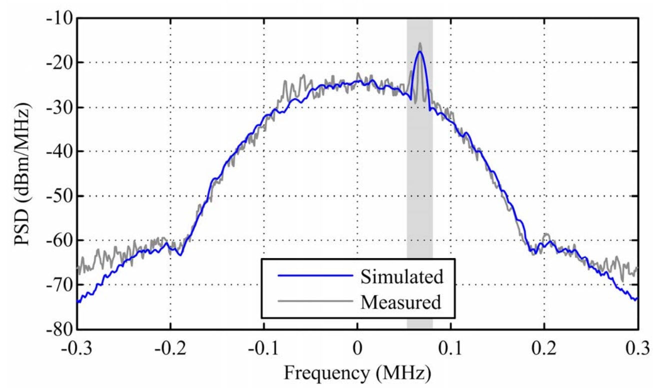

Figure 4. Power spectral density (PSD) versus frequency for simulated and measured broadcast signals. The tone generated during a frequency correction burst is indicated in the highlighted region.

IV. Clock Harvesting Receiver Architecture

In this section, a receiver architecture is proposed to detect the FB (frequency correction burst) and use its periodicity as a clock source for the wake-up of sensor nodes. This architecture is designed to harvest only the FB clock and not provide the full functionality of a GSM radio. The goal of this architecture is to harvest a clock by measuring the total power of the BCCH carrier and comparing it to the power measured at the FB offset frequency. During a frequency burst, these two measured powers will be equal. At all other times, the power at the FB offset frequency will be less than the total channel power. The wake-up clock then is harvested by detecting when these two powers are equal.

The proposed architecture to implement this is shown in Fig. 5. A RF front-end down-converts the GSM signal to a

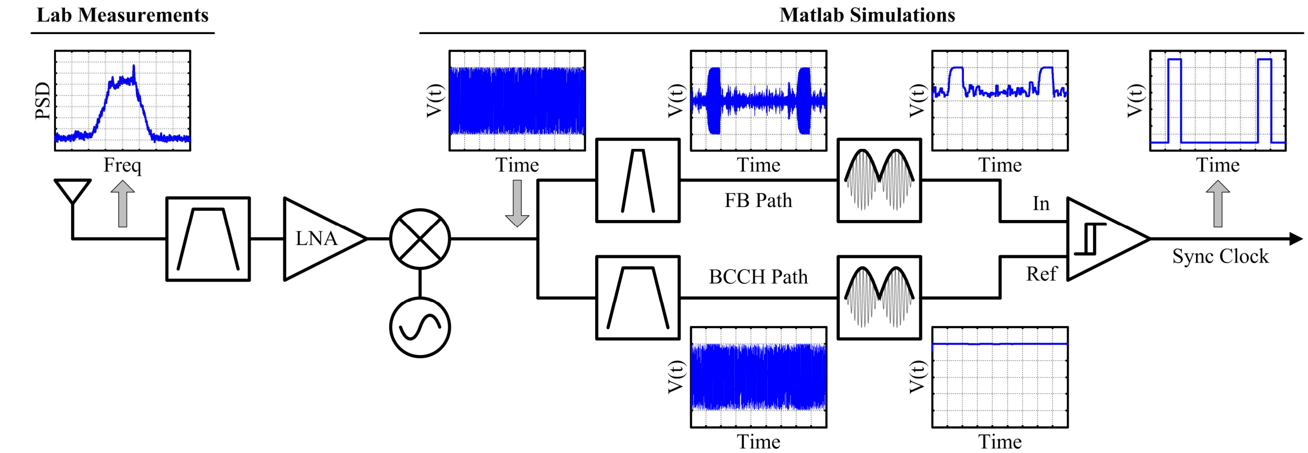

Figure 5. The proposed architecture for a clock harvesting receiver. The broadcast channel is mixed down to a low intermediate frequency, then split and run through FB and BCCH filters before the signals are peak-detected and compared to generate the digital clock output.

low intermediate frequency (IF). Assuming the front-end can be realized with a low-power architecture similar to [5], then the front-end could consume as little as 52 µW. Following down-conversion, the signal path is split into two filters. One filter passes the entire BCCH carrier, while the other selects a narrow bandwidth around the FB offset frequency. Because a GMSK signal has a constant amplitude, the signal power can be measured by envelope detection. Therefore to measure and compare the power of the BCCH and FB filters, the outputs are envelope-detected, and the envelopes are compared with a thresholding comparator.

Plots along the signal path are shown in Fig. 5 to illustrate the functionality of the proposed receiver. A GMSK-modulated signal at IF is shown at the output of the RF front-end. This signal is passed through the BCCH and FB filters, so that the frequency correction bursts become apparent at the output of the FB filter. The signals then are peak-detected to extract the envelopes. Finally, a clock is produced at the output of the thresholding comparator.

In this system, the BCCH filter should pass the entire channel bandwidth, while the FB filter bandwidth must be carefully chosen to ensure a low probability of error when harvesting the clock. The only signal desired at the output of the FB filter is the tone generated during a frequency correction burst. Any other signal seen at the output of this filter will be appear as pseudo-random noise (PN) generated by the GMSK-modulated data. Therefore, we can analyze this system in terms of a signal-to-noise ratio (SNR) by treating the FB as signal and PN data as noise. We then can choose the optimal FB bandwidth to maximize SNR, given the energy constraints to realize the filter. Therefore, our goal is to jointly minimize the probability of synchronization error and power.

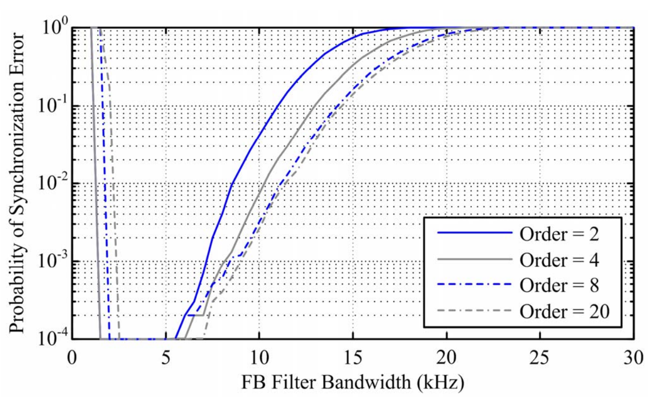

Figure 6. The probability of a synchronization error versus the bandwidth and order of the FB filter.

V. SIMULATION RESULTS

To analyze the performance of the FB filter, the architecture shown in Fig. 5 was simulated in Matlab with a GSM-modulated signal input at IF. This signal consisted of periodic frequency correction bursts separated by GMSK-modulated PN data to model the data transmitted on the BCCH carrier. For the simulations, the BCCH filter was a fixed 2nd-order Butterworth bandpass filter with a 200 kHz bandwidth centered on the channel while the FB filter was a Butterworth bandpass filter centered at the FB offset frequency. Both the bandwidth and order of the FB filter then were swept while the output of the harvested clock was compared with the true FB repetition rate. Finally, the number of errors was counted, where an error was defined as either not detecting a clock edge during the beginning of a FB burst or detecting any number of clock edges between bursts.

The results from these simulations are shown in Fig. 6, According to these results, the probability of synchronization error decreases as the FB filter bandwidth decreases. Below a filter bandwidth of 5 kHz, no errors were detected over 10^4 FB intervals. This corresponds to over 10^8 GMSK symbols. As the filter bandwidth is reduced below 2 kHz, there is a sharp increase in the probability of error. This is the result of two effects: 1) the FB filter is now attenuating the tone burst, and therefore, SNR at the output of the filter no longer improves; and 2) the power of the signal observed through the FB filter is decreasing relative to the power observed through the BCCH filter. Therefore, a FB filter should be chosen with a bandwidth greater than 2 kHz to avoid this sharp increase in probability of error.

The probability of synchronization error also decreases as the order of the filter increases at a fixed bandwidth. This

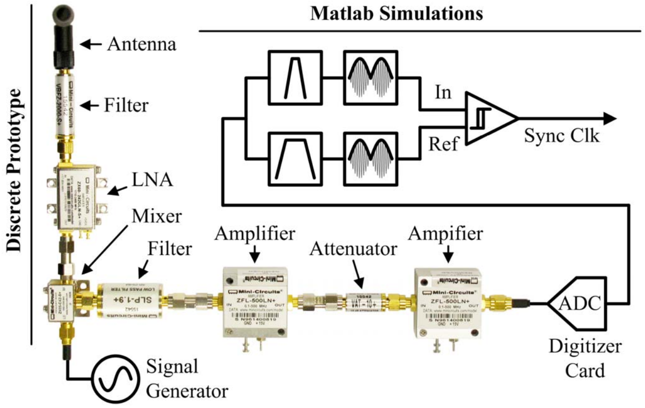

Figure 7. A discrete prototype for a clock harvesting receiver, consisting of a bandpass filter, LNA, mixer, low-pass filter, and IF amplifiers.

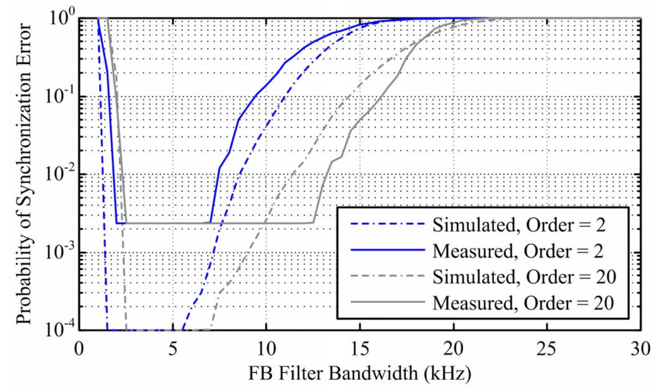

Figure 8. The probability of synchronization error versus FB filter bandwidth and order for both simulated and measured GSM signals.

improvement in synchronization error due to increased order is limited to an order of approximately eight. Increasing the filter order beyond this does not improve performance.

The simulation results suggest that we should choose a FB filter bandwidth of around 4 kHz and an order of 8 to achieve a low probability of synchronization error. When implementing this filter in hardware, narrower bandwidths (higher quality factor) and higher order both correspond to higher power requirements [8]. Therefore, for the lowest power wake-up radio, the widest bandwidth and lowest order FB filter should be chosen for a given target probability of error. For example, for a target probability of error of 10^{-3}, a 2^{nd}-order filter with 7 kHz bandwidth is sufficient (Fig. 6).

VI. Discrete Prototype Results

A discrete prototype was built as a proof-of-concept to demonstrate that a clock could be extracted from a local GSM cell signal (Fig. 7). The prototype consisted of an antenna, band-select filter, low-noise amplifier, and mixer, which down-converted a BCCH carrier from the 1900-MHz GSM band to an IF of 275 kHz. The IF signal then was low-pass filtered, amplified, and digitized with an 8-bit analog-to-digital converter at 1 MS/s. The digitized data then was processed in Matlab using the receiver architecture shown in Fig. 5. The FB filter bandwidth and order were swept again using the measured data for the input signal, and the resulting probability of synchronization error was compared to the prior simulation results.

A clock was successfully harvested from the measured signal with some probability of synchronization error. These measured results are compared with simulated results in Fig. 8. The same general trends are observed between the sets of results; the probability of synchronization error of the measured data decreases with decreasing FB filter bandwidth and increasing filter order. Furthermore, at a given FB filter order, the filter bandwidth required for low probability of error is sufficiently predicted by the simulation results.

Conclusions

A technique for harvesting a clock from the GSM cellular network was introduced. This clock can be used as the beacon signal for wake-up radios in a wireless sensor network. The advantage of this approach is that the signal is pre-existing and pervasive; therefore, the network does not have to generate it, conserving energy. An architecture was proposed to harvest this clock using only filters and a thresholding comparator. Functionality was verified with a discrete prototype by extracting a clock from a measured GSM signal. When combined with a RF front-end such as [5], this architecture is suitable for the wake-up of ultra low-power sensor nodes.

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