The FindIT Flashlight: Responsive Tagging Based on Optically Triggered Microprocessor Wakeup

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Abstract. We have designed an active tagging system that responds to a coded optical beam from several meters away. The tags contain a minimalist microprocessor that ambiently operates in shutdown mode and, upon detecting particular frequency components in the AM-modulated interrogation beam, awakens to decode the incident digital message and produce an appropriate response. The lack of linear amplifiers means that these tags draw under 0.5 μA when sleeping, hence can operate up to 10 years on a lithium coin cell. Such devices are practical demonstrations of the potential of ubiquitous computing where common, nearly passive objects have a sense of identity and the ability to respond to external stimuli. In our example, the interrogator is a "flashlight", with which one scans an area; when the light beam hits a tag programmed with a code that matches that sent by the interrogator, an on-tag LED flashes, indicating that the desired object is "found".

1) Introduction and Motivation

A prime goal of ubiquitous computing [1] is the embedding of sensing, communication, and computation into everyday objects. One consequence of this paradigm is that perhaps nothing will be lost again, allowing us to gain rapid access to the objects we want. This is particularly important in the age of digital storage media, where information content is often not obviously expressed by the appearance of packaging. The mechanical constraints of CD's, DVD's, MiniDV's, etc. means that their content is abstracted into or scrawled onto anonymous, homogeneous containers. This is even true of books. How many times have we stared at a shelf full of books in the library only to find what we are looking for half an hour later?

The motivation behind the tagging system described in this paper is to find a practical way to give everyday objects a sense of identity and the ability to decide how to respond to external stimuli. The ideal tags for this application should be completely passive and last forever. The tag should produce an apparent response for a positive or negative identification when interrogated with a coded message from several meters away. The interrogation unit should also be power efficient, such that it can be integrated into a handheld device like a Palm Pilot or iPAQ.

Barcode scanning systems were developed to keep track of large collections of objects. However, one problem in using barcodes is that the read distance is generally well within a meter. For even small collections of objects, bar-code scanners simply cannot compete with the speed at which a human can find things. Furthermore, printed barcodes can degrade quickly due to mechanical abrasion and UV light.

Various RF and nearfield electromagnetic schemes have been developed for identification and tracking of objects. Commercial RFID passive tagging systems [2] are widely adopted, and operate by powering the tag circuit through a magnetic, electrostatic, or RF field broadcast by the reader. The read range tends to be limited for these systems (e.g., under a meter for the nearfield devices and several centimeters for handheld units), and the tags generally don't harvest sufficient power to make any kind of local, physical response via activation of an LED or piezoelectric buzzer. RFID tags generally respond by modulating the reader field or by transmitting a very low-power signal of their own. An exception to some of these caveats can be found for some microwave tags – here a focussed antenna forms a beam that energizes a passive tag via an onboard rectenna. The formation of a directed beam bears some similarity to our flashlight scheme, and microwave tags can have read ranges of up to several meters. Our optical flashlight reader tends to form a much tighter beam (at least compared to handheld microwave systems below 5 GHz), and the visible nature of the optical interrogation lends a more direct correspondence to the goal of searching for a particular item; one sees clearly where one is looking. Although conventional microwave tagging systems still don't impart enough energy to the tags to illuminate a local LED, researchers have developed higher power systems that can do this [3], eliminating the need of a battery. Safety considerations, however, preclude widespread adoption of this technique.

Another possibility is to mount a battery on the tag, which would enable the tag itself to give an occasional active visual or audio response. Active receiving tags have been used for several well-known ubiquitous computing demonstrations – perhaps the most common are infrared (IR) badges [4] used to locate people in a building. The IR receivers, however, consume considerable power, as they must remain continuously active to detect the transmitter's code.

Battery powered tagging systems are not entirely out of the question for this application, given that many microprocessors have a shutdown mode in which they use negligible amounts of power. Using the technique presented in this paper, it is possible to keep the microprocessor ambiently in shutdown, and wakeup when the signal of interest is present. If we can stretch the net battery lifetime to be greater than the maximum lifetime over which we are interested in the tagged object, we can consider these tags to be equivalent to a passive approach.

Tags that employ an active receiver need a linear amplifier, which requires that the batteries operating them need to be periodically recharged or replaced. The lower limit of tags using linear amplifiers is about 150μW, which, for example, would last less than 2 years on two AAA batteries.

An optical tagging method using photovoltaic cells as a receiver and a light beam as the interrogator is desirable because the cells can easily harvest power from the interrogation beam. Since the ambient optical environment is relatively free of sharp edges, pulse-coded optical transmission can attain a relatively high signal-to-noise ratio and wake up the processor without the use of linear amplifiers. A passive high-

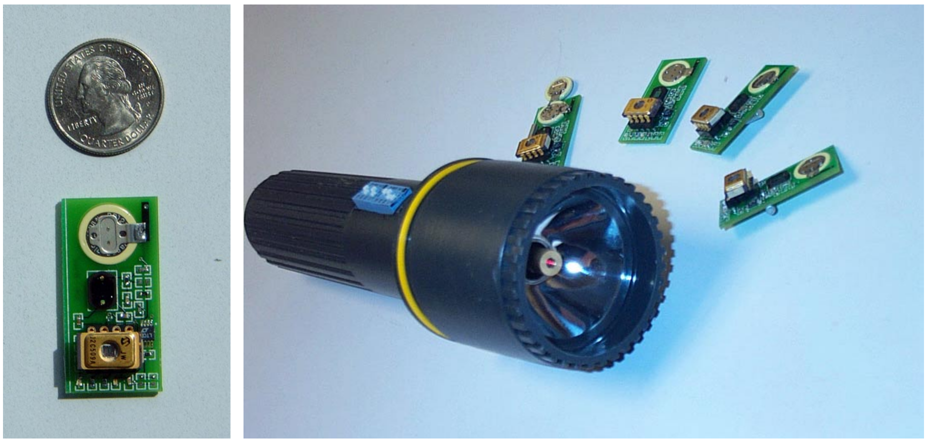

Fig. 1. Tag (with DIP-8 PIC12C509 shown here) and flashlight transmitter-interrogator

pass filter and low-power comparator suffice to produce a robust wake-up trigger from the photodiode output (the same components are also capable of discriminating the data bits broadcast by the interrogator). Bright optical sources such as LED's and diode lasers can be operated on very little power, forming a "flashlight" interrogator that would be compatible with handheld devices. Finally, photo detectors, low-power comparators, and minimal microprocessors are inexpensive; therefore the entire system can be made at low enough cost to be truly ubiquitous.

2) Technical Design

We have designed a tagging system based on interrogation by a coded optical message (Figures 1-3). As seen in Figure 1, the tag is built on a printed circuit measuring 4 cm by 2 cm and, with all components mounted, is approximately 6 mm thick. Note that this board is still a development device; a surface-mounted microprocessor and tighter layout can make the tag much smaller. The tag circuit is composed of a small lithium coin cell, silicon photodiode, high-pass filter, nano-power comparator, and minimalist PIC microcontroller (Figure 2). The microcontroller ambiently operates in shutdown mode and wakes up upon detecting the high frequency pulses present in an incident message. The microcontroller is currently programmed to decode a 2 kHz, 8-bit signal. The amount of time required to wake the microprocessor from sleep mode is approximately 18 ms and an additional 4 ms is required to decode the 8-bit, 2 kHz code sequence, bringing the total response time to approximately 22 ms. Although the prototype transmits and decodes 8-bit sequences, the system easily scales up to 32 or 64 bit codes with only modest compromise in response time (e.g. 0.5 ms per bit; the data rate could also be much faster, bringing this interval down even further).

The photodetector is a 0.2" square silicon photodiode [5]. The photodiode is optimally loaded with a 15kΩ resistor to produce the largest possible amplitude for

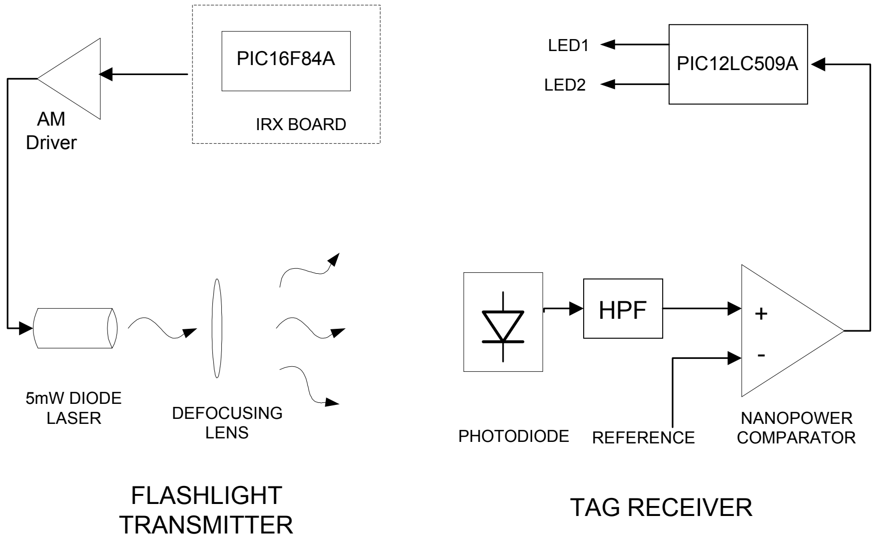

Fig. 2. System block diagram

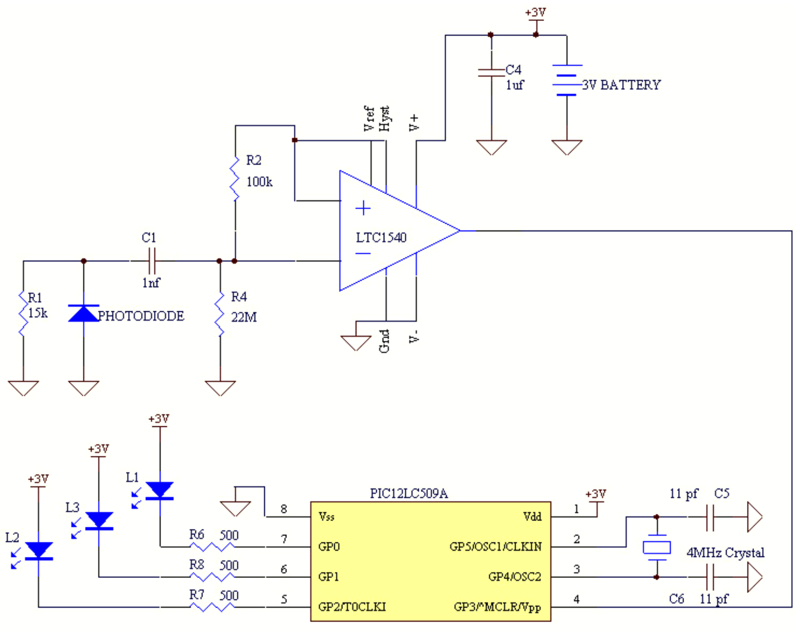

Fig. 3. Tag receiver circuit

2kHz modulation. The incident signal is high-pass filtered to eliminate the effects of ambient or 60-Hz light and provide wakeup triggering when the interrogation beam hits the photodiode. The filter time constant is chosen to be much greater than the total period of the interrogation message, in order to pass the bits intact. This circuit is

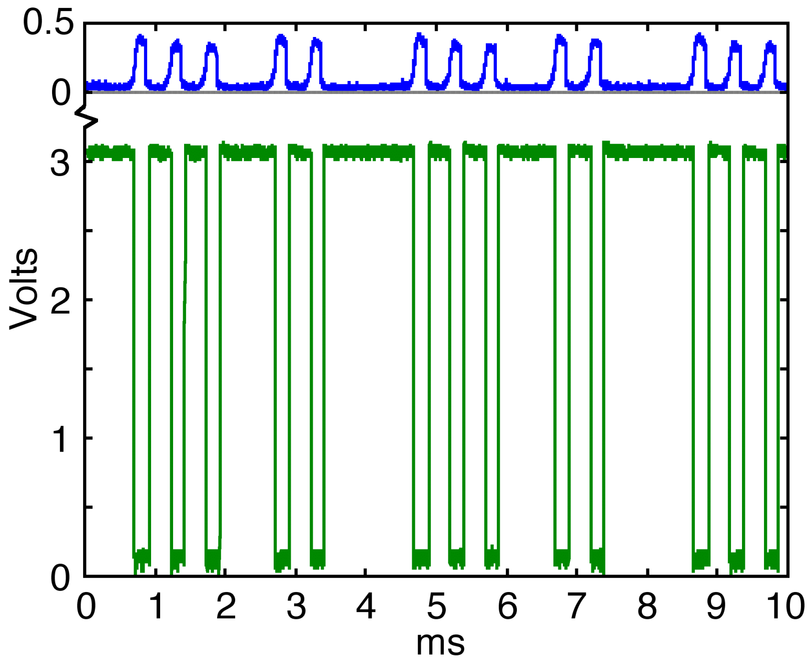

Fig. 4. Tag receiver signals. Top trace – photodiode signal, Bottom trace – comparator output

also insensitive to common dynamic light sources, such as fluorescents. As seen in Figure 3, the LT1540 nano-power comparator from Linear Technologies [6] is used to produce the correct logic voltages for the PIC microcontroller, evident in Figure 4. The LTC1540 provides a 1V reference, which can source or sink up to 1mA of current. R2 and C1 are used to set the time constant of the input filter, while the resistive divider of R2 and R4 sets the triggering threshold on the incident signal. The total sensitivity of this system is eventually limited by the input offset voltage properties of the comparator. The LTC1540 quotes a maximum offset of 16mV.

The minimalist 8-pin microcontroller, PIC12LC509A from Microchip [7], is the processor chosen for the tag. This device can be operated on as little as 2.5V, and when in shutdown mode, draws a measly 200nA. In the tag circuit, the PIC12LC509A operates ambiently in shutdown mode and is set to wake on an edge at one of its input pins fed by the comparator. After the microcontroller has woken up, the output from the comparator becomes the message that the microprocessor will decode. If the correct message has been identified, then the microprocessor responds by flashing a green, low-power LED. A low-power piezoceramic buzzer can also be used to produce audio feedback.

The battery used for the tags is a Panasonic BR1225 lithium coin cell. This battery produces an operating voltage of 3V at a nominal capacity of 48mA-h. The total current draw in shut down mode is 500nA, with 300nA coming from the comparator and 200nA from the microprocessor. At this rate, the battery life is approximately 10 years - essentially its shelf life. Upon positive identification of a signal, the average current draw, dominated by the LED, is 2mA for a period of 10 seconds. This

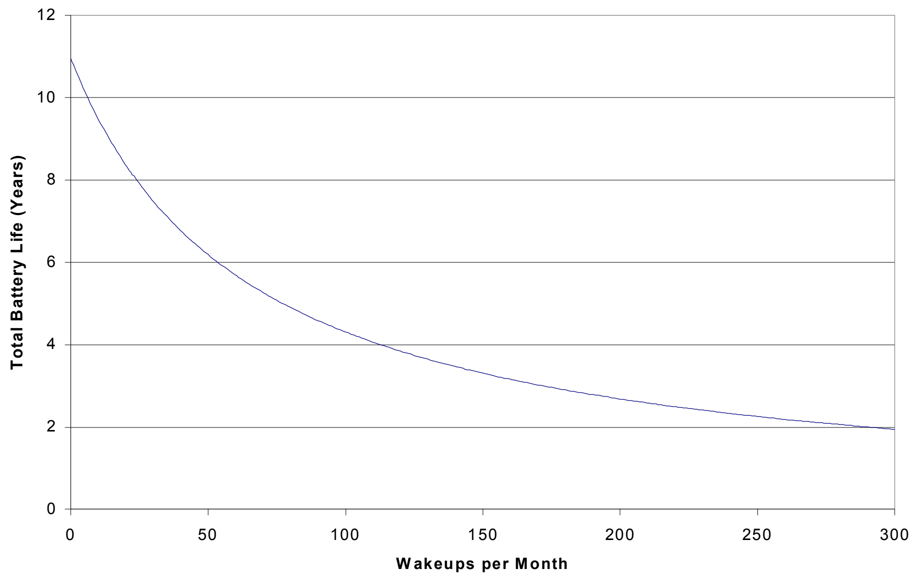

Fig. 5. Total Battery Life vs. Number of Matched Wakeups per Month

indicates that each tag can be identified a total of 9000 times before its battery fails. Figure 5 shows a plot of the expected battery life vs. the number of matched wakeups (where the LED activates) per month based on these parameters; with modest use, this battery will last many years.

The coded message transmitter (or interrogator) is a diode laser powered by a standard 9V battery. The diode laser is a 5mW red diode laser, as commonly found in laser pointers. The laser lens is modified and defocused to produce a 5cm diameter spot from 3m away. The large spot size is necessary to reduce the pointing accuracy required to locate tags and to make the system completely eyesafe. Note that the laser is not necessary in this application; a properly collimated beam from an array of bright LED's would work as well.

The message is modulated at 2kHz by a MOSFET switch controlled by a Media Lab IRX utility board [8] (containing a PIC16F84A processor) mounted in the interrogator "flashlight", seen in Figure 1. Although the current prototype uses a dipswitch to program its interrogation message, in practice such a device would be programmed via a more convenient means (e.g., wireless connection to an external application, an on-board display interface, integration with a PDA, etc.). The total power drawn by the transmitter is easily compatible with handheld computing devices; the microprocessor draws 10mA, while the laser itself uses approximately 50mA.

This optical tagging system has a range of at least 3m, and it is independent of ambient illumination level. Two LED's are involved in our prototype tags: one (a red LED) illuminates when the tag is woken up, and another (a green LED that contrasts very well with the red laser) flashes when an ID match is found. In practice, the red LED is unnecessary, and can be omitted to save power.

The incident message is transmitted via 2 kHz square waves. The communication scheme uses on-off keying (OOK) on half of the transmitted waveform. This approach is designed to make it easy for the tag to synchronize to the transmission. The serial decoding scheme relies on precise timing of the PIC microcontroller. The PIC12LC509 is clocked 4MHz and has a 1MHz instruction cycle. The decoding algorithm runs as follows. First the program synchronizes itself to the transmission and the beginning of a code by finding a transition from 0 to 1. Then, the program begins to accumulate bits. Once enough bits have been accumulated, for each additional bit received, the program rotates through its receive buffer to check if the right code has been received. When the correct code is found, the program jumps into a subroutine to flash the LED connected to its output pin. Due to the asynchronous nature of our communication protocol, rotationally equivalent codes cannot be uniquely identified. Therefore, as predicted by the Necklace Theorem [9], our 8-bit system has exactly 36 independent codes (35 usable codes since the all-zero code cannot be detected), where as a 32 bit system would have approximately 70 million independent codes.

3) Discussion and Conclusion

We have designed a micropower responsive tagging system based coded optical interrogation, and have demonstrated it as a "flashlight" that can search for items with digital content that matches a code broadcast by the optical beam. Although such a system has many applications relevant to ubiquitous computing, one scenario that has motivated this development is the labeling of electronic media such as removable disks, CDROMs, DVD's, flash chips, etc. We've all encountered the problem of poorly-written labels adhered to these packages that have little room to properly annotate the digital content (many of us are forced to repeatedly insert the storage media into a reader in an attempt to find the desired files). By mounting one of our tags onto the media cartridge, it can be read when the media is written, and the tag's ID associated with the content that has been stored. Accordingly, the interrogator can subsequently be programmed with this ID via a database program when one desires to find this file again, and the interrogator's beam can be swept across the cartridges stored, say, on a set of shelves, rapidly finding the desired unit when the corresponding tag activates.

As the tag is essentially always in shutdown mode (drawing under 300 nanoamperes), it has a shelf life approaching that of the onboard battery, provided it isn't read (and matched) extremely often. In this fashion, one can scan the visible light beam across the shelves, looking for the particular disk as if you're searching for something in the dark. The flashlight effectively does this digitally - it exposes virtual parameters of the objects that are intrinsically hidden until uncovered via the interrogator. Although a similar system could be designed with microwave tagging technology, the tags and the interrogator would probably be considerably more complicated and expensive; likewise the optical system involves no microwave emission, plus affords a visible beam, directed as tightly as desired, so one can easily see exactly where the search is occurring. The downside of this system is that it requires an optical line of sight between interrogator and tag, but as the main output of the tag is likewise optical via LED's, the line of sight is still required.

As the response of the tag is relatively fast (e.g., 22 ms), the tags are able to be read when the interrogator beam is moved quickly across them, just as it a flashlight beam would be naturally scanned when searching in darkness. As most practical systems will require more bits in the ID code to distinguish more objects, upgrading to a faster data rate (easily attainable) will enable this prompt response to be maintained.

With some refinements in the system design, we believe it is possible to reduce the shutdown-mode current draw of the tags even further, down to the level of 100nA. This circuit would likely involve a single-chip solution integrating and customizing the photodiode, comparator, and microprocessor. Such an approach would also reduce the size of the tag to the size of the battery.

4) Acknowledgements

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