Real-Time, Automatic Animal Tracking Using Direct Sequence Spread Spectrum

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***Abstract*— A method for tracking animals using a terrestrial system similar to GPS is presented. This system enables simultaneous tracking of thousands of animals with transmitters that are lighter, longer lasting, more accurate and cheaper than other automatic positioning tags. The technical details of this system are discussed and the results of a prototype are shown.**

I. Introduction

Radio-tracking has been widely used to monitor wildlife movements since the 1960s with hundreds of scientific papers published using some variant of this method. Early applications of the technique include [1] and [2]. For the majority of these studies, an operator monitors received signal strength while changing the orientation of a directional receiving antenna. The direction yielding the maximal signal strength is recorded as a pointing vector to the tagged animal. This simple method is adequate to guide a researcher to the location of a focal individual, and triangulation using two or more receiving stations can be used to track a few individuals simultaneously. The accuracy of this method is detailed in [3]. However, this method yields relatively few position fixes per hour, and fully absorbs an operator's attention and effort. Automatic tracking systems have been developed using fixed receiving towers [4], [5], [7]. Most efforts involve directional antennas and rely on the beam pattern of the antennas to infer a direction of arrival. These approaches generally suffer an error in the 1-10 degree range, depending on the implementation [6] and the cross-bearing positional error for each receiving station increases linearly with range.

In addition to terrestrial radio-tracking methods, two satellite based options exist: GPS and Argos. These two systems provide location information using different techniques. GPS employs a network of orbiting satellites that broadcast signals to a terrestrial receiver which uses a Time Difference of Arrival (TDOA) algorithm to estimate its position. The Argos system exploits the frequency shift in the received transmission (Doppler shift) caused by a satellite's motion relative to a transmitter on the earth. The principle drawback of GPS is that it does not directly provide a means of reporting position information back to the researcher. The position information is either stored and retrieved later, or downloaded via an auxiliary radio frequency link. Weight is also a limiting factor for satellite-based systems. The typical maximum allowable tag to body weight ratio is 5%, with lower being preferable. The smallest GPS tags at present are in the 22 to 150 gram range, which limits their application to larger animals (>440 g). The Argos system can achieve reasonably good accuracy; the best service available advertises 150 m accuracy. However, this level of accuracy is not often available, and the other three accuracy classes range from 150 to 1000 m. Argos tags are generally smaller than GPS tags, but still only allow tracking of animals heavier than 200 g. This weight constraint excludes 40% of all bird species. The cost of GPS and Argos tags is also prohibitive for large-scale studies. The complexity and low volume of these tags lead to typical single unit prices in the $1500 to $4000 range, with little cost reduction at larger volumes.

The weight, cost, and performance of existing radio-tracking techniques necessitate a new approach. We have designed, built and installed a prototype system based on Code Division Multiple Access (CDMA) and Time Difference of Arrival (TDOA) that is capable of automatically locating thousands of tags in real time.

II. System Design

A. System Overview

Previous attempts at terrestrial automatic radio tracking have relied on conventional, fixed frequency, narrow band transmissions. These transmissions carry relatively little information for the power consumed during transmission. In contrast, our approach relies on a new, broadband transmitter that emits a transmission modulated with a unique pseudo-noise (PN) sequence. This approach is similar in many ways to a GPS system operating solely in acquisition mode. The transmitted sequence occupies a typical bandwidth of 2MHz and lasts about 3 msec. Each transmitter operates on the same carrier frequency, which is currently 140MHz, but each transmitter modulates that common carrier with a different PN code. We have chosen Gold Codes for the system, due to their attractive cross-correlation properties. This yields a code division, multiple access system: many transmitters can operate simultaneously without significant interference. The receiver, unlike a conventional animal tracking receiver, "listens" continuously to the 2MHz wide bandwidth that the transmitted signal occupies and runs a matched filter detector. When a signal is detected, the receiver precisely timestamps the event and sends a data packet to a server with the event ID, tag ID, time and other information. The server accumulates these individual data packets from different receivers, which are located in different positions, and groups receive events. When multiple receive events correspond to the same transmission event (the tag was “heard” at multiple receivers), the server computes a position estimate. Three or more receivers must receive the same transmission in order for the server to compute an accurate position fix. If only two receivers hear the transmission, the transmitter position can be limited to a particular hyperbola, and if only one receiver hears the transmission, a simple presence/absence data point is available.

The system uses precise timing of receive events to calculate transmitter position. One major benefit of this approach is that the accuracy of the system does not degrade as a direct function of distance, unlike the Direction Of Arrival (DOA) based systems. Significant power savings, relative to conventional techniques, are also realized by this approach. Very short and infrequent transmissions are possible because the receivers are listening constantly, and can listen for transmissions from all tags simultaneously. Conventional radio tracking tags transmit for 30 msec and repeat every 2 to 3 seconds. This transmission length and interval are the minimum allowable times for a human operator to accurately discern a reception event and determine tag direction. However, in our system the tag can be configured to transmit for only 3 msec and repeat only as often as independent position fixes are required. For example, it is entirely possible to transmit once every 5 min, which reduces tag power consumption by a factor of 1500. This dramatic reduction in consumption enables multi year studies with transmitters similar in mass to conventional tags. If maximum tag lifetime is not a priority, lower power consumption can also enable lighter tags. Our tags are easily programmed, in contrast to conventional radio tracking tags, which must be custom-built for a particular frequency and cannot be readily modified.

B. The Transmitter

The transmitter (tag), shown in Fig 1, is based on an inexpensive, very low power microcontroller, along with a separate PLL, mixer and amplifier. Our design integrates off-the-shelf ICs in order to avoid the high cost and long development time of a custom ASIC. This choice results in an implementation that is larger than it could otherwise be, but this tradeoff allows rapid development. The tag uses a binary phase shift keyed (BPSK) modulation scheme to directly modulate and spread the carrier power, as shown in Fig 2. The modulation rate is 1MHz, resulting in a 2MHz wide main band. The tag is programmable for center frequency, transmission interval, pseudo-noise code, chip-rate, RF output power, and operating schedule. This programmability allows tailoring the tag parameters to the application, which maximizes lifetime for a particular tag mass. The current tag mass is 1.4g without the battery and encapsulation. Future versions will reduce mass by 50%.

Transmitting an RF signal is the most power consuming operation for any small transmitter. In conventional tracking systems, many of these transmissions are not used because the receivers are not capable of simultaneous multi-channel operation, and because the human operator requires multiple transmissions to determine a bearing, and multiple bearings to determine a location. In contrast, the automatic detection algorithm running in our receivers is capable of determining tag location from a single transmission. This capability enables a very low duty cycle, dramatically increasing tag lifetime.

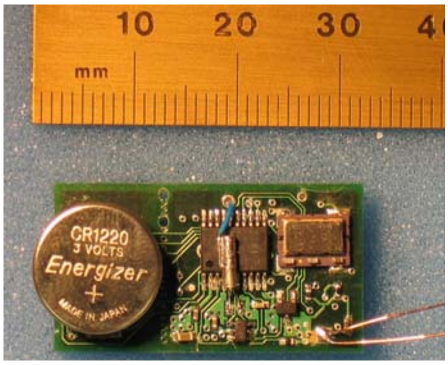

Fig. 1 Transmitter board, with typical battery and programming tab still attached

Each tag sends two PN sequences, one after the other, per transmission interval. The first sequence is common to all the tags and serves as an acquisition and synchronization signal. The second sequence is unique to each tag and encodes ID. Each sequence is chosen from the family of Gold [8] codes available from an 11 bit generator. Gold codes are attractive due to their predictable cross-correlation performance and relatively easy generation. This particular family of codes supports $2^{11}+1$ individual IDs. This allows 2049 animals to be simultaneously monitored, an order of magnitude more than other systems.

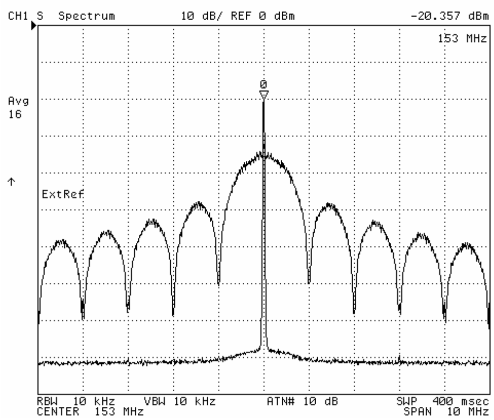

Fig. 2 Transmitter output showing unmodulated and modulated carrier

C. The Receiver

The receivers use a method similar to GPS in order to automatically locate animals wearing our tags. Each receiver runs a real time, matched filter detector that enables them to continuously monitor all possible tag PN codes. The receivers “listen” for the initial synchronization code by performing an operation similar to that of a GPS receiver in acquisition mode. This involves a two dimensional search in offset frequency and code phase space, known as an ambiguity function search. The incoming signal and the template to be matched must be correlated for each code phase and frequency offset. We have simplified the problem however by eliminating the requirement to search in frequency (Doppler) space. This can be avoided by keeping the length of the code short, relative to the frequency difference of the reference clocks at the tag and receiver. The receivers use a GPS disciplined frequency reference which offers sufficient accuracy, however the tags clearly cannot carry a GPS receiver. Inexpensive and accurate TCXO clocks provide the tag reference frequency. Typical tolerances for these clocks are 1-5ppm, corresponding to an offset of 140 to 700Hz at 140MHz. The expected value of the base band signal as a function of carrier phase ($\Delta\theta$), code phase ($\Delta\tau$), and frequency offset (Δf_D) are shown in (1) [9].

$$E\{S\} = \sqrt{C}De^{j(\Delta\theta+\pi\Delta f_D T_{CO})}\,\bar{R}(\Delta\tau)\mathrm{sinc}(\pi\Delta f_D T_{CO}) \quad (1)$$

The sinc function component can be thought of as an amplitude modulating factor; larger values of Δf_D or T_{CO} reduce the amplitude, which reduces the signal to noise ratio. While the total tag sequence is 3 msec long, the synchronization and ID codes are processed as separate halves, which yields an integration time, T_{CO}=1.5 msec. If we set $\Delta f_D <= 1/2T_{CO}$, then for the coherent integration time of approximately 1.5 msec, Δf_D can be as large as 333 Hz. Birds carrying the tags will not be moving fast enough to induce an appreciable Doppler shift, therefore this result allows us to avoid the computationally expensive task of searching the ambiguity function in frequency space, provided that the oscillator reference is not worse than 3ppm.

Once the receivers have detected the synchronization code, they then search the next 1.5 msec of signal for all possible ID codes. This search can be done efficiently, since the phase of the code has just been determined. A GPS module in each receive station allows the receivers, which are in different locations, to precisely record the arrival of each synchronization code.

The matched filter detector offers another advantage in addition to precise time-stamping: it allows us to realize significant signal processing gain. The pseudo-noise code modulation at the transmitter spreads the transmitted energy out over a 2MHz wide band. At the receiver, the matched filter detector de-spreads the signal, effectively reducing the in-band noise, and increasing the signal to noise ratio. This approach allows us to detect signals that are 20db below the background noise floor. Conventional receivers, with a human listening to the receiver output, can reliably detect a signal that is 6 to 8 db below the noise floor. This improved sensitivity enables greater reception range, relative to traditional receivers. The present system can operate with a tag to tower range of up to 7 km in deciduous forest. Thus, a regularly spaced grid of receivers is required for covering larger regions. Improvements in range, based in increased processing gain and reduced interference are ongoing.

The attractive features of this system, including low power tags, automatic detection, and improved location accuracy, depend on a network of receivers that can listen continuously and in real time for tag transmissions. The real time requirement sets a hard limit on performance which impacts all other design choices. We chose to implement the matched filter detector on a Texas Instruments TMS320C6416 Digital Signal Processor. This processor can run at 1GHz and offers parallel data processing capability, with up to 8GMAC per second when operating on 8 bit data. The incoming RF signal is down-converted to base band I and Q channels and then sampled at 2.8125 MHz. An 11 bit PN sequence at the tag's 1MHz chip rate would occupy 5760 samples, and processing the I and Q channels with a straightforward, time-domain matched filter implementation would require approximately 32 GMAC per second in order to guarantee real time operation. This requirement clearly cannot be met, even by the impressive performance of the 'C6416, which was state of the art when this work began. The options available are to either reduce the bandwidth of the transmitted signal, which reduces the ranging accuracy, reduce the PN sequence length, which reduces the processing gain, or to use a frequency domain algorithm to implement the matched filter. We chose this alternative, and used available FFT routines along with the well known practice of performing a convolution by multiplying in the frequency domain, to meet the real time requirements of the system.

D. Networking, Data Processing and Storage

In addition to the DSP and GPS module, each receiver contains an embedded Linux Single Board Computer (SBC) which is used to capture DSP detection strings through an RS-232 interface. Multi-threaded Python code parses the serial input and attempts to submit the data via an Ethernet link to a remote server. The Ethernet port on the SBC is connected to a GSM modem with a crossover cable. This enables wireless Ethernet connectivity within the Cingular/AT&T service area. If no Ethernet connectivity is available or data submission fails, the records are stored locally in non-volatile compact flash within an SQLite database. Stored records are periodically checked, and submitted when a connection to the server is established. Data records are bundled and zlib compressed for submission over a TCP stream to the server. The Twisted Python networking library was used to write a TCP server process and protocol that is capable of handling simultaneous data streams from many receive stations. The server process receives batches of compressed data events and submits them into the central PostgreSQL database for localization and analysis.

III. SYSTEM PERFORMANCE

We installed a four receiver system in Ithaca, New York to test and validate our approach. Table I shows the results of a five minute long static test conducted near the center of the array. A GPS was used to survey the location of the tag and the locations that the GPS and the Auto-locating system reported are given. Fig. 3 shows a histogram of the estimated

Easting (x) coordinates from this test. We captured six American Crows and affixed the tags using a backpack style harness (Fig. 4). The tags were configured to transmit once per second, in order to ensure sufficient data for post-processed analysis. The data for the arrival time of each tag were aggregated in a database and then processed with MATLAB scripts. The computed locations were then overlaid on Google maps-based images as shown in Fig. 5. The positions of the receivers are indicated with orange circles, and the track of the crow is shown with a red dashed line. This information can be updated in real time.

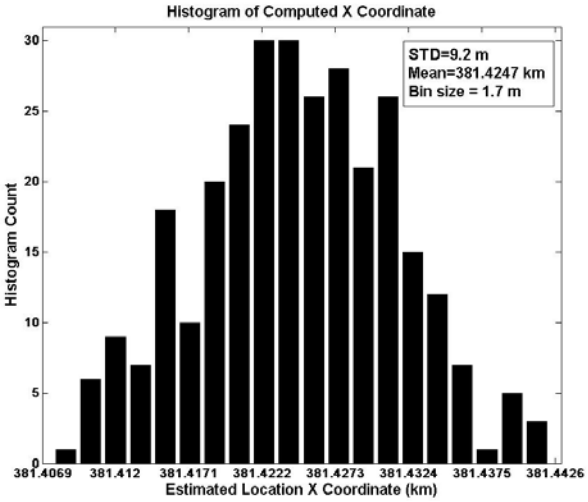

Fig. 3 Histogram of computed Easting (x) Coordinate

Fig. 4 American Crow with prototype DSSS transmitter

Fig 5. Track of Crow WJ

TABLE I
TEST RESULTS FOR FIXED TRANSMITTER

	GPS	Auto-Locating System	
	Avg Pos (km)	**Mean Pos (km)**	**STD (km)**
Easting	381.426	381.425	0.0091
Northing	4700.084	4700.065	0.0089

IV. CONCLUSIONS

Though time tested and relatively simple, conventional radio tracking techniques are not suitable for monitoring large numbers of animals over long time scales. They are labor intensive, yield relatively few position fixes per unit time, and use their batteries inefficiently. Existing automatic location tags based on GPS and ARGOS are too heavy for many birds. We have demonstrated a system for tracking large numbers of animals accurately over medium ranges. The transmitters are very small, making them suitable for most birds and can last several years.

ACKNOWLEDGMENT

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