CARNIVORE: A Disruption-Tolerant System for Studying Wildlife

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***Abstract*—This paper presents CARNIVORE, a system for in-situ, yet unobtrusive monitoring of cryptic, difficult-to-catch/observe wildlife in their natural habitat. CARNIVORE consists of a network of mobile and static nodes that have sensing, processing, storage, and wireless communication capabilities. One of CARNIVORE's notable novel features is its robustness to intermittent node connectivity since, depending on the wildlife being studied, the network can be quite sparse and therefore disconnected frequently for arbitrarily long periods of time.**

Field tests show that the "collar" can transmit data at 60 kbps within a range of 50-200 meters. Its Li D-cell battery provides the collar with a lifespan of 50-100 days during which it can collect and transmit 1GB of data. The latest version of the CARNIVORE node has been packaged in a collar and deployed on mountain lions. The collected accelerometer and GPS data shows that the system is a viable and useful tool for wildlife research.

I. Introduction

Known broadly as biotelemetry, remotely monitoring organisms has proved to be a powerful tool in understanding their physiology, behavior, and ecology [1]. Biologists have long recognized the need to study free-ranging animals in their natural environment. However, many species are cryptic and wide-ranging, and thus difficult to monitor directly or capture for repetitive physiological measures. To overcome these challenges biologists have long used VHF radio tracking [2] and archival data loggers on free-ranging animals [3].

New technologies have improved the effectiveness, efficiency, and ubiquity of biotelemetry. Increases in energy density of batteries and greater system miniaturization has allowed placement of VHF transmitters on the smallest mammals and large insects [4]. Researchers have also used the ARGOS satellite system for sensor data transmission, including highly accurate global positioning system (GPS) locations. In addition, VHF or UHF radio-modems are used to download data directly by the researcher. Unfortunately, ARGOS has very low data rate capabilities over a simplex data channel ($1.5 - 7.2 kbits\ day^{-1}$) [5]; and radio-modems have yet to be automated, requiring the researcher to manually download data. And while they have ranges on the order of 10 km, they have a data rates of 9.6 kbps.

Advances in wireless communications, VLSI, and Micro-Electro-Mechanical Systems (MEMS) have enabled networks of low-cost, small form factor sensing devices which will bridge an important gap in the current biotelemetry state-of-the-art. Due to their ability to sense, process, and communicate sensed data, sensor networks make sensed data readily available to scientists (and the community at large), in real-time (or quasi real-time) at low cost and with the required spatial and temporal resolution.

In this paper, we present the Carnivore Adaptive Research Network in Varied Outdoor Remote Environments (CARNIVORE), a sensor network system that specifically targets wildlife monitoring. CARNIVORE was born out of an urgent need to gain deeper understanding of the interplay between predators, their ecosystem, and encroaching human populations. It is largely motivated by the ever increasing expansion of urban development into wildlife habitats and illustrated by an increasing number of interactions between wildlife and humans [6]. Predators also can exert heavy pressure on their prey species, sometimes reshaping their own ecosystem [7],[8]. The extent of pressure a predator puts on prey is directly linked to its energetic requirements for survival and reproduction. A firm understanding of their physiology and energy budget calls for high resolution behavioral and physiological data. This data can be difficult to collect for predators that are hard to capture and time consuming to monitor directly. Also, relatively rare but important events such as mating or consuming prey may be missed when animals are unobserved. Here we present early results from data collected on mountain lions (*Puma concolor*). We also present results of further testing and analysis of the accelerometer data, GPS, firmware, network protocol, and power consumption.

The contribution of our work is the design of the CARNIVORE system starting from system objectives, describing hardware component and software algorithm selection to meet said objectives, and presenting experiences associated with testing and deploying the system. We present the system objectives in Section II. Section III discusses the hardware components of the system. Section IV outlines the system firmware while Section V goes into detail on the network component of the system. We present our findings and results in Section VI and then conclude the paper. Though there is no related work section, we mention related work throughout the paper where relevant.

II. System Overview

CARNIVORE's design was customized to fulfill the unique requirements imposed by wildlife monitoring applications including: energy efficiency, ability to operate with episodic connectivity, and reliability by being able to store data locally (when connectivity to a data sink is unavailable). The resulting CARNIVORE monitoring network architecture consists of both mobile sensing– and fixed relaying nodes which provide sensed data to biologists wirelessly, eliminating the need to recapture the predators. The net effect is considerable reduction of the delay between data collection and data delivery, and increased effectiveness of data collection.

The CARNIVORE mobile, animal-borne, sensing nodes, or CSNs, are limited in weight, yet contain the required sensors (3-axis accelerometer and GPS), processing, storage, and communications capability. Each CSN must be capable of providing data that will allow biologists to monitor the physiology and behavior of the target species. Of particular interest is their hunting habits and energetic costs. In order to accurately track the animal's energy budget, its behavior can be categorized into activities such as walking, running, sleeping, hunting, feeding, and so on. Furthermore, the footfall frequency in any gait is obtained and can be used to calculate the expended energy. Acceleration data along three axes will be used to extrapolate behavior data such as activity and footfall pattern [9],[10]. After local, as well as centralized processing at the information sink(s), raw data will be turned into behavior and energetics data. Coupled with GPS position fixes and time stamps, we can put this data in perspective against other factors in the ecosystem such as human populations, habitat types, and other animals of the same– or different species.

Weight and power constraints have the biggest effect on design choices. With batteries as the single heaviest component, power is one of the system's most limited resources. Thus communication, processing, sensing, and data storage must all be optimized to minimize energy consumption and extend the operating life of each node. Furthermore, CSNs' storage capability should be carefully provisioned so that the system can withstand operation under episodic connectivity and still meet the specified data reliability requirements.

Coyotes (*Canis latrans*) were chosen as the first target species for developing the CARNIVORE network; however, the system is flexible enough to be used on a variety of species. During development of the platform, research focus has switched to mountain lions and the system is currently deployed on mountain lions in the Santa Cruz Mountains for first field testing. The first fully-functional version of the CSN was developed by Petkov [11]. This first version of the collar allowed for substantial testing of the system, especially with respect to the accelerometer and real-time system (RTS) firmware.

The design of the CARNIVORE network allows for opportunistic data flow between CSNs and from CSNs to SRNs (Figure 1). CARNIVORE static relay nodes (SRNs) communicate with CSNs acting as data sinks, capturing data collected by CSNs. Wireless links between CSNs and CSNs-to-SRNs utilize the 802.15.4 MAC layer and a CARNIVORE specific network protocol. In future versions of the SRN, they can provide wider-range network connectivity and convey sensed data out of the network. Although the upper, SRN-tier of the network has yet to be implemented, we anticipate robust power supplies and long-range communication links for these nodes.

III. Hardware

The CARNIVORE CSNs were designed from the ground up with the goal of maximizing battery life while meeting the application goals. Dictated by the CARNIVORE application requirements, the hardware specification for sensing and data storage of the CSN could not be met by existing solutions such as the Berkeley Mote platform [12],[13],[14]. Specifically, this platform was very early in its design when we began CARNIVORE and could not meet our requirements with respect to storage and low-power wireless. The components for the CARNIVORE platform were chosen to meet the sensor and long-lifespan requirements proposed by the biologists (Figure 2). Components were chosen with low-power operation in mind to maximize collar lifespan and minimize weight through smaller batteries. The GPS provides location and velocity data while the accelerometer can provide data to monitor activity and behavior of the target animal. The MSP430 microcontroller [15] provides numerous attractive characteristics with respect to code memory, peripheral modules, and low power operation. Individual modules can be turned off when not in use to minimize power consumption.

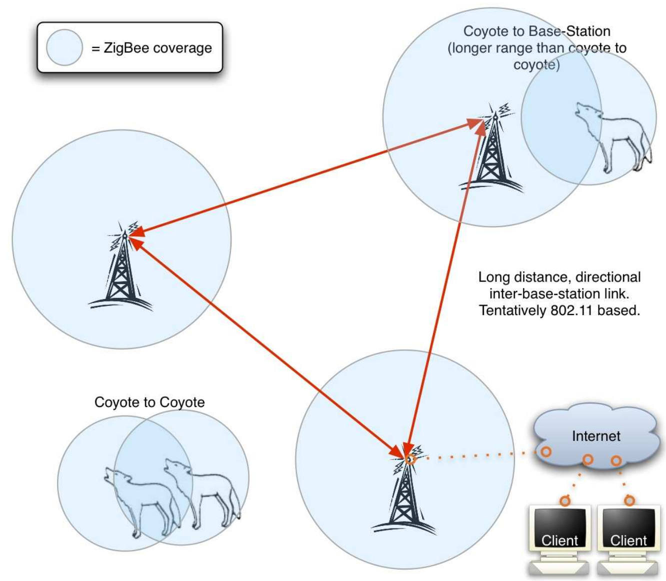


Fig. 1. Overview of the CARNIVORE network. Predators carry CSNs and SRNs serve as base-stations.

The deployed CSN (Figure 3) also included off-the-shelf components to guarantee tracking and recovery of the CSNs in the event of a total system failure for first field deployments. The timed drop-off was made by SirTrack [16] and causes the collar to fall off the animal at a specified date and time. The VHF beacon was produced by Telemetry Solutions [17] and was used to locate collars at long range (0.1 - 20 km). Both devices had separate power supplies and were fully independent of the CARNIVORE system.

A. Transceiver

An early version of the CARNIVORE node [11] used a transceiver module with a full ZigBee protocol stack. The interface was unwieldy and added a second microcontroller, which increased power consumption. By implementing a custom CARNIVORE network protocol and the 802.15.4 MAC layer on the MSP430, power consumption was reduced, the

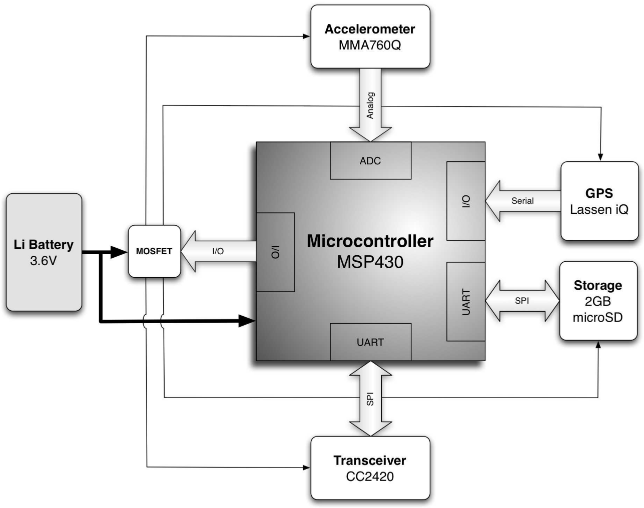


Fig. 2. Top level block-diagram of the CARNIVORE hardware. Black arrows indicate power connections. Thick, shaded arrows indicate control and data connections.

Fig. 3. Picture of deployed CARNIVORE node. The CARNIVORE electronics are above, D-cell battery and VHF beacon are lower-right, and a timed drop-off (SirTrack [16]) is lower-left. Components were assembled by Telemetry Solutions.

footprint of the radio reduced, and data transfer rate was increased by reducing the network overhead.

The CC2420 transceiver and associated balun circuit were laid out as shown in an Ember application note [18]. A folded-F printed circuit board (PCB) antenna was used to minimize cost of the design [19]. Performance is comparable to surface-mount, chip antennas. If the PCB size must be reduced for future designs, a chip-mount antenna can be used and easily incorporated.

B. Power supply

By using 3.6 V Li batteries with a very flat voltage profile, no power regulation is required. Lithium batteries at 3.6 V are available in D, C, AA and other sizes and so this design will be able to accommodate a variety of form factors and sizes of batteries for small and large animals. A design without voltage regulators reduces power consumption because regulators are less than 100% efficient. Dual MOSFETs were used to control power to individual components, allowing them to be turned off individually when not in use.

IV. Firmware

The firmware of the CARNIVORE platform is interrupt driven and centers around a simple scheduler [11]. This framework has made substantial modifications easy to make during design iterations (Figure 4). Tasks are arranged in an array of function pointers, where each task is assigned a single element in the array. Tasks are started when an interrupts adds a task into the scheduler by inserting a function pointer into the high- and low-priority task arrays. Each state in the state machine is a function where the function pointer for the next state is inserted into the task arrays. When the task is done, a null-pointer is inserted into the array so the task is no longer continued. Tasks in the low- and high-priority arrays are processed in a round-robin scheme. In each pass through the main loop, one function for each high priority task is called while only one low-priority function is called.The network and MAC sub systems will be discussed in Section V.

In the early design stages, we made a difficult decision between completely custom firmware and TinyOS [20]. A flexible embedded operating system such as TinyOS provides a modular interface between software and hardware and takes on the burden of managing system resources and scheduling execution – all desirable attributes.

A flexible OS comes with a price however. For example, cpu cycles and memory need to be allocated to inter-process messages and operating system state variables. Each OS function must come at the expense of complexity (and thus increased power consumption). With the CARNIVORE CSNs, simplicity was chosen over flexibility to allow minimal power use and meet a design goal of non-stop 100Hz accelerometer sampling. The system functions entirely around interrupt-based cues allowing it to meet its real-time requirements.

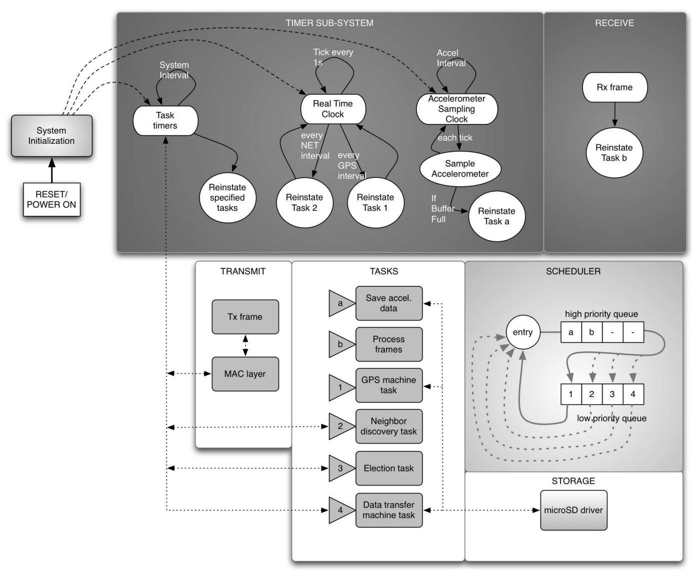


Fig. 4. Top level block-diagram of the CARNIVORE firmware.

A. Data storage

During initial debugging of the firmware, a FAT file system on the SD card was valuable for testing sensor data acquisition. However, troubleshooting file system errors became difficult to debug and the FAT file system was replaced by a system of FIFO queues. Four queues are available so each data type (accelerometer and GPS) and data source (local or exotic) can be prioritized for forwarding through the network.

New data collected at the node or received from other nodes are enqueued at the tail of the appropriate queue. To allow for the multi-copy forward routing (Section V-E), data sent to other CSNs can be dequeued from the middle of a queue. Only when data is sent to base station is data dequeued from the head pointer. If the head pointer catches up to the middle pointer, the middle pointer is moved along with head pointer. This allows for multiple copies to be forwarded through other CSNs to the base station while the originator of the data maintains a local copy for eventual download to the base station.

B. Accelerometer firmware

Timing information in the header for the accelerometer data allows for 1/1000th second accuracy for each accelerometer sample. Each accelerometer data segment contains 12 bytes of time-stamp and 110 3-axis accelerometer samples. The timing information in the header refers to the first accelerometer sample in the data segment. The 12-bit accelerometer data is packed in half-bytes to fully utilize the memory space and data payload. At a user defined interval, an interrupt triggers the capture of an accelerometer sample. Sampling rates of over 100Hz were achieved while still meeting all system timing requirements.

C. GPS firmware

The GPS firmware allows for network timing by updating the nodes system time and maintaing an accurate real-time clock for sensor sampling. In addition, the GPS firmware ensures that the Lassen iQ's [21] almanac is always current. Time, latitude, longitude, altitude, and velocity are recorded for each GPS fix.

V. Network Protocol

The CARNIVORE network can be considered a highly-disconnected network or a usually-disconnected network because predators wearing the CSNs are typically not within wireless range of each other. Timely or complete recovery of the data at a base station is not required; however, as much data as possible should be captured. There are three tasks which set-up the inter-CSN connections: neighbor discovery, election, and data transfer (Figure 5). Each of these utilizes the MAC layer to send and receive data. A single MAC layer task parses frames rapidly and updates the state variables for the neighbor discovery, election and data transfer tasks. A routing table is maintained with each neighbor to a CSN. When two or more nodes come together, they form a star shaped network where the central node is chosen to receive the data from all the other nodes (6). If present, a SRN is always chosen to receive data, otherwise a CSN is chosen as the central node. This central node mediates the round-robin scheme and minimizes competition for the channel, giving each node a request for data in turn (See Sections V-D and V-E).

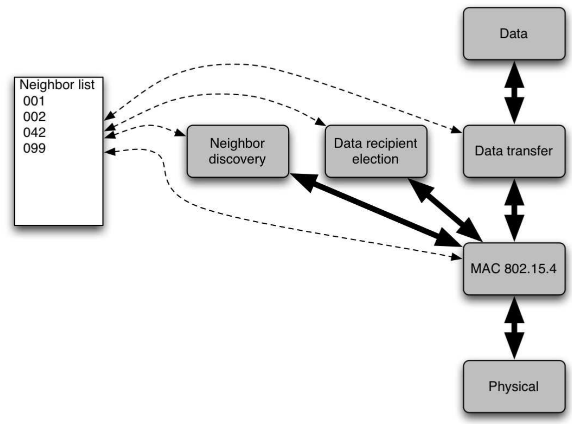


Fig. 5. Network stack and associated data structure. The CARNIVORE stack uses a routing table of neighbors. The list is populated during neighbor discovery and updated by various layers. Received frames are processed in the MAC layer which then updates the neighbor list.

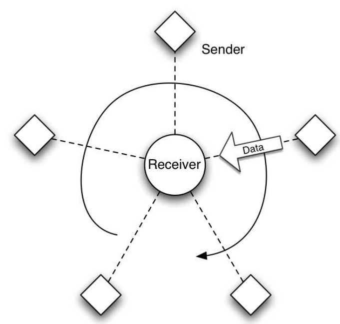


Fig. 6. Round robin star network. The receiver mediates the round-robin data transfer, accepting data from the senders. Either sender or receiver can end the transfer.

A. Disruption-Tolerant Routing

The low density of collared coyotes, the speed at which they can travel, and home ranges of $10-300km^2$ necessitates a disruption-tolerant data routing approach. In contrast to traditional routing protocols in which connectivity between any two nodes is generally assumed, a disruption-tolerant routing protocol must employ the long-term storage capabilities of each node to cooperatively route messages toward their destination (in this case, the fixed base stations).

An early approach to routing in such networks, Epidemic Routing [22], functions by replicating all messages to all nodes in the hope that one or more of the copies will reach the destination. More recent projects such as ZebraNet [23] and DieselNet [24] have explored routing between zebras and city buses respectively. Research on Data MULEs [25] explores topologies in which sensors are static devices, and a mobile node (a MULE) provides connectivity to a destination node.

CARNIVORES presents a unique networking challenge due to some of the characteristics of the collars, in particular, the large amount of storage space available in comparison to their limited bandwidth. Each CSN produces data at a rate of 2.1 kbps, and can store 2GB (approximately 88 days worth) of data. However, since it can be transmitted at a maximum rate of 63 kbps with relatively large power use compared to base-line power use, care must be taken to use the available bandwidth efficiently.

B. MAC layer

The current version of the CARNIVORE CSN utilizes a custom network protocol stack and implements a simple CSMA/CA MAC with the IEEE 802.15.4 radio [26].

C. Neighbor Discovery

The first step in the network protocol is to wake-up synchronously, announce yourself, and find your neighbors. The GPS time signal keeps all nodes synchronized. Each node sends out non-acknowledged beacons to the broadcast address with their node ID and a metric to be used to select the data recipient (see Section V-D). Fifteen beacons are sent out at pseudo-random intervals to minimize collisions and guarantee a large amount of overlap when nodes are sending beacons. Each received beacon updates the neighbor list. If neighbors are found, this task puts itself to sleep and wakes the election task.

D. Election of Data Recipient

In order to determine which node should receive data, a metric that correlates to likelihood of reaching a SRN is used. This type of routing is known as directed diffusion broadcast routing, where packets do not have a destination address and are simply forwarded along a direction or gradient most likely to result in delivery [27]. In the CARNIVORE network, the gradient is controlled by a saturating timer that is reset to 1 whenever a node encounters an SRN. The node with the lowest metric has most recently visited a base station. And since nodes are on predators assumed to have stereotypic behavior, this node should be the most likely to encounter a base station again. This method was simple to implement and was found in simulation to work better than a random choice of receiver. SRNs are assumed to never be in wireless contact and always have a metric of 0 and thus always act as a receiver.

Nodes choose the neighbor with the lowest metric to receive data (Figure 7). If their own metric is the lowest, they wait for a nomination. If they do not have the lowest metric, they send a nomination packet with an acknowledge request to the node with the lowest metric. The nominee must send a nomination acceptance packet back for a link to be established. In this way, a hidden node will not disrupt the formation of a network (Figure 7). An ignored nomination will cause the nominating node to timeout. It will not attempt to initiate another link until the next network wake-up. Also, a node waiting for nominations but receiving none will also timeout and must wait until the next network wake-up. A nominee becomes the receiver in the data transfer task. All nodes that sent nominations and received acceptances become senders in the data transfer task. Nominations and acceptances are each attempted three times.

E. Data Transfer

Simulation of the CARNIVORE network showed that a multi-copy-forward scheme performed the best with respect to delivery success and minimizing total transmissions but at the cost of buffer space. Since we are using 2 GB microSD cards, buffer space is not a problem and this strategy was chosen. In multi-copy-forward, a copy of data is stored locally on the generating node and a single copy is forwarded through the network. This part of the CARNIVORE network protocol, as well as data prioritization, is accomplished when a sending node chooses which data to send.

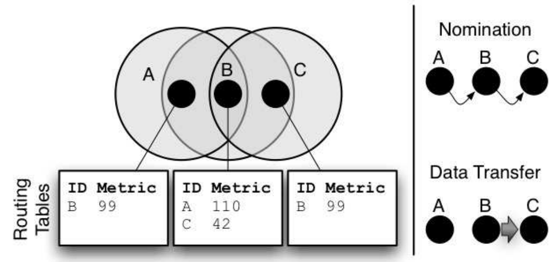


Fig. 7. Hidden-station example. Radio range is shown by the shaded circles. A nominates B, B nominates C, and C nominates itself in the election. B ignores A's nomination and A times-out. C accepts B's nomination. B then sends data to C and A does not transmit any data during this network wake-up.

The receiver first checks if it has room for any more data. If yes, the receiver sends a data request and starts a short timeout. Upon receipt of the data, the receiver moves onto the next node and requests data. If a timeout occurs or an end-of-data packet is received, that neighbor is removed from the neighbor list. The receiver limits each node to sending a maximum number of data segments such that the round robin will end before the next network wake-up. The receiver terminates a link with a node by not sending a data request and letting that node timeout. All packets are sent with an ACK request and attempted three times. After a third failure, the neighbor is removed from the neighbor list.

The sender during data transfer sets a long timeout and waits for a data request from the receiver. This long timeout allows for one complete round-robin with the maximum number of nodes in the round-robin. Once a data request is received, the node picks a data type to send. If no data of any kind is available, the sender sends an end-of-data packet to terminate the transfer. If the node has data to send, it fragments the 512 byte data segment into 6 packets to accommodate the 128 byte maximum data size specified by the 802.15.4 standard. These packets are then sent with an ACK request in a typical stop-and-wait scheme. As with the receiver, all packets (except ACKs) are sent with an ACK request and attempted three times. If they fail, the data is restored to the queue and the node ends the transfer.

Using these schemes for sender and receiver, situations where nodes move out of range are handled gracefully. In addition, any collected data on a collar is not lost when packets are lost in transmission.

VI. Experiments and Results

A. Power

Current consumption was measured for hardware components using a 1Ω current sense resistor and a Tektronix

TABLE I
DEPLOYED FIRMWARE SETTINGS AND BATTERY POWER.

Component	Value
1 Li D-Cell	19 Ah
GPS sampling interval	20 min
Accelerometer sampling rate	60 Hz
Network wake-up interval	5 min
Estimated lifespan	100 days

TABLE II
MEASURED POWER CONSUMPTION AND PERCENT TIME ACTIVE PER COMPONENT FOR THE DEPLOYED SYSTEM.

Component	Current drain (at 3.6V)	Percent time active
Transceiver	23.0 mA	1.0%
GPS	41.4 mA	3.8%
GPS SD card access	22.5 mA	<0.1%
μC and accelerometer	5.8 mA	100.0%
Accelerometer SD card access	25.0 mA	1.4%
AVERAGE	7.9 mA	

TDS3054C oscilloscope. Temporary changes were made to the firmware to enable or disable various components of the system. Voltage across the resistor was measured and converted to current using Ohm's law (Tables II). In addition, the amount of time each module was active was measured with the oscilloscope or calculated from firmware settings. These values could then be used to calculate the expected lifetime of a CSN given a battery with a specified Ah rating using equation 1 (Table I):

$$L = \frac{A}{24 * \sum_{C}^{i=1} c(i) * p(i)} \tag{1}$$

where L is the CSN lifetime in days, C is the number of components, $c(i)$ is a components current consumption in mAh, $p(i)$ is a components percent time consuming current, and A is the mAh rating of the battery.

To confirm this method of estimating lifespan, we performed an accelerated power test. We modified the settings of a CSN to sample GPS and attempt a network connection more often. We used 2 AA Li 1.5 V batteries to power the CSN. This produced a much greater total power consumption 38.0 mA and allowed us to drain the batteries in a relatively short time period – one that confirmed the estimate. We predicted the CSN would last 3.3 days. From the GPS and accelerometer data logged by the CSN, we found the actual lifespan was 3.4 days.

B. Wireless Radio Link

We performed a variety of range tests in an open field with waist to head-high vegetation. By using specialized firmware, we were able to record the success rate of frames sent between nodes. Figure 8 shows that CSN-to-CSN communication performs reasonably well through and over vegetation. For the deployed system on mountain lions, biologists will approach the animal and manually download data with a hand-held SRN. Thus maximum range was needed. We equipped an SRN with a $12dBi$ high-gain directional antenna and saw a much improved range for the CSN-to-SRN. An extended range of approximately 150 m proved adequate to approach a mountain lion and download data from its CSN.

Sensor data was transferred between collars less than 10 m apart at 63 kbps. This did not include network overhead. This data rate is approximately 30 times the rate at which data is collected by a CSN sampling the accelerometer at 60 Hz. Thus a CSN need only spend $\frac{1}{30}$ of its time near a SRN to download all it's data.

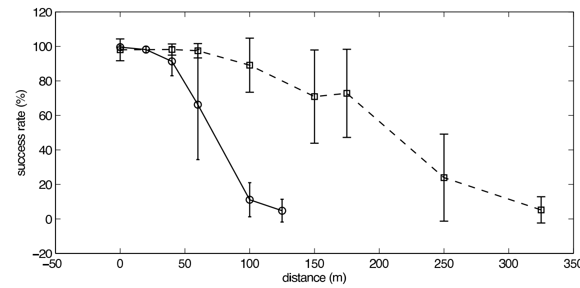


Fig. 8. Range test results for CSN-to-CSN (solid line) and CSN-to-SRN (dashed line). Bars indicate one standard deviation.

C. Data Collection Trials with Domestic Dogs

We used a domestic dog (Pippin) on a treadmill and running next to an electric cart to test the accelerometer. We analyzed this data to verify that stride frequency observed in video recordings of these trials matched the frequencies found in accelerometer data. In addition, we confirmed that frequency is correlated to speed for different gaits as was shown by Heglund [28] (Figure 9). This shows that speed of the collared predator can be determined from the accelerometer record if gait and stride frequency can be identified.

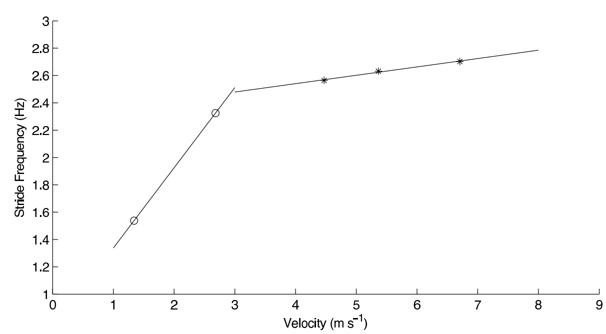


Fig. 9. Stride frequency and velocity of Pippin. Circles indicate a walking gait and asterisks indicate a galloping gait. Lines indicate best-fit linear regression for each gait.

D. AMDF Analysis

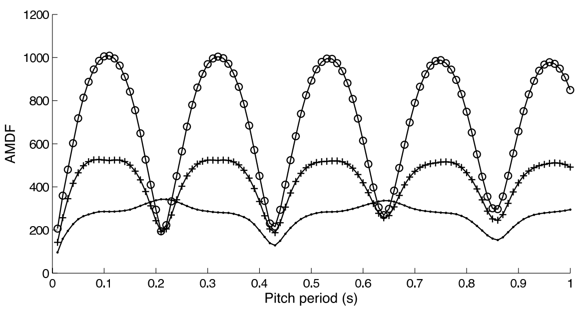
In order to determine the gait and stride frequency of an animal form the accelerometer record, we looked for auto-correlation in the time domain using the average magnitude difference function (AMDF):

$$AMDF(t) = \frac{1}{L} \sum_{L}^{i=1} |s(i) - s(i-t)| \tag{2}$$

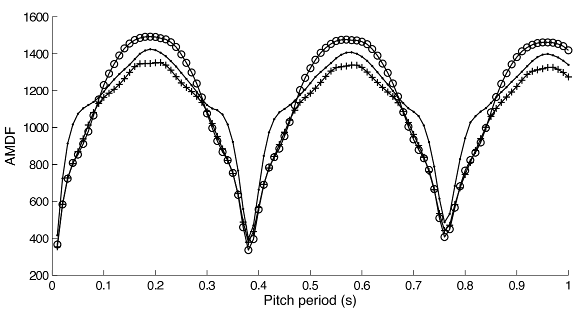
where t is the period in seconds, L is the window size of the data to be examined, and s(i) is a normalized sample [29]. Periodicity in the signal is identified by minimums in the

AMDF function. We chose this function because it can be computed with integer calculations, primarily multiplications, and a minimum of division operations. Looking to the future where behavior may be identified in real time on CSN, the AMDF function is a good candidate for an MSP430 based embedded system with a hardware multiplier.

Using the AMDF function to analyze data from several trials of Pippin that were also video taped, we were able to confirm that stride frequency and gait can be determined from the accelerometer data (Figure 10). There are two obvious characteristics of the AMDF function that differentiate walking from galloping. The first is the shape of the head-to-tail axis. Its shape is very different between galloping and walking. Furthermore, the amplitude of the AMDF function is much larger when Pippin is galloping. By comparing the observed stride frequency from the video to the AMDF function, it appears that the first minimum shared by all 3 axes is the stride frequency of the gait.



(a) Pippin walking on the treadmill at $6mph$.



(b) Pippin galloping next to the cart at $12mph$.

Fig. 10. AMDF functions for accelerometer trials with pippin. Three accelerometer axes are shown: vertical (circles), side-to-side (pluses), and head-to-tail (solid).

E. Test Deployment

In order to test the deployed system, a network of three nodes was set-up. A domestic dog and a human carried CSNs and a single SRN was placed at Long Marine Lab, Santa Cruz, CA, USA (Figure 11). Data was successfully transferred between all CSNs to the SRN, both directly and indirectly through an intermediate node.

F. Deployment on Mountain Lions

In the fall of 2008, the CARNIVORE system was deployed on mountain lions (*Puma concolor*) in the Santa Cruz Mountains, CA, USA. This research is ongoing but early results indicate that CARNIVORE will enable researchers to monitor the behavior of these apex predators. To date, we have deployed 3 collars and have collected 15 days of accelerometer and GPS data from one collar. Because mountain lions range widely, a portable SRN was used to download data from the mountain lion. Early analysis of both GPS (Figure 12) and accelerometer data (Figure 13) indicate that both location and acceleration data for the animals is successfully being recorded. An important next step in the development of the system, is to observe the mountain lions carrying CSNs in order to correlate the accelerometer record with specific behaviors.

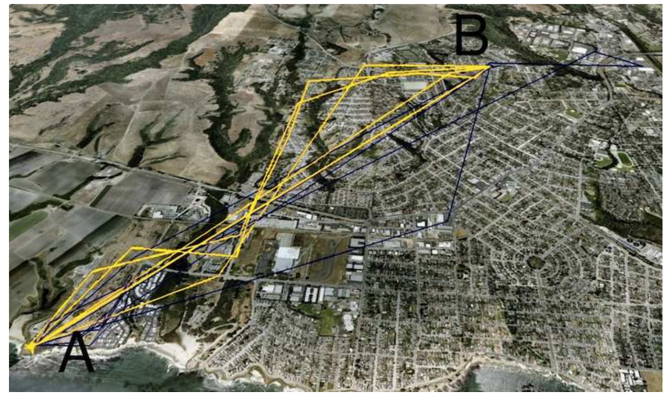


Fig. 11. GPS data from the test deployment. The dark track is the dog's GPS data, the light track is the GPS data of its owner. A SRN was located at A. The dog lived at B and his owner worked at A.

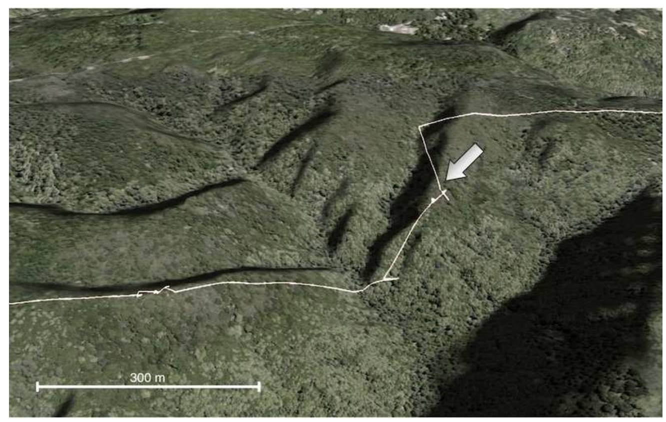
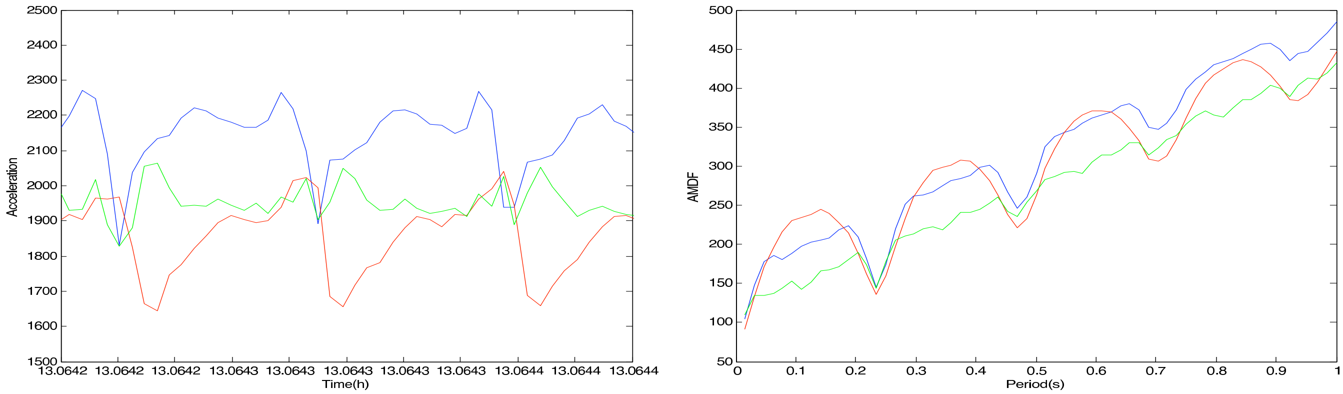


Fig. 12. Subset of mountain lion GPS data. This data was collected on October 17. 2008 from a CSN on a mountain lion in the Santa Cruz Mountains, CA, USA. Arrow indicates an event with periodic accelerometer data. See Figure 13.

VII. Conclusion

A. Current Wildlife Telemetry Technology

The only comparable system to CARNIVORE, with inter-collar networking capability, is ZebraNet [23]. The ZebraNet collars where much larger than CARNIVORE collars, weighing 1151 g compared to 450 g for the collar designed for mountain lions. Such a large collar would be unsuitable for many terrestrial predators and would not support high data rate sensors.



(a) 0.72s of raw data around 13:00 GMT

(b) AMDF.

Fig. 13. Accelerometer data and AMDF analysis of mountain lion data from October 17, 2008.

Compared to commercially available wildlife tracking collars that allow for remote download, the CARNIVORE platform can deliver a much greater quantity of data. A state-of-the-art GPS tracking collar of similar weight to the CARNIVORE collar with remote download (Quantum 5000 - Telemetry Solutions [17]) can record and transmit 15,000 locations over its lifetime. At 30 bytes per location, this is 450 kB of data compared to 1 GB of data for the CARNIVORE platform.

The early results from deployments on Mountain Lions indicate that the CARNIVORE is a viable research tool. Furthermore, system tests prior to deployment and this first field test show that CARNIVORE is a viable option to gather data in a highly-disconnected system. At under $1000 per CSN, compared to $2000-4000 for commercial collars, the CARNIVORE network will prove to be a valuable and affordable tool for wildlife biologists to ask and answer interesting questions about cryptic predators.

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