A Sensor Based Tracking System Using Witnesses

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***Abstract*— Search and rescue of people in emergency situations, e.g. lost hikers, stranded climbers, or injured skiers has been difficult due to lack of information about their location at various times. Current location and tracking systems require a connected network via satellites, GSM base stations, or mobile devices. This requirement severely limits their applicability, particularly in remote wilderness areas where maintaining a connected network is very difficult. This paper proposes a new tracking system called Cenwits that is based on sensors that use RF for communication and emit beacons from time to time. When two sensors are in the range of one another, they record the presence of each other and exchange the information they recorded earlier. A sensor dumps all its information to an access point, whenever it is in the range of one. Important advantages of Cenwits include a loosely-coupled system that does not require network connectivity, power efficiency, and low cost. A preliminary prototype of Cenwits is being built using Berkley Mica2 Motes. The paper reports results from this preliminary prototype.**

I. Introduction

A major application area of pervasive computing systems is keeping track of the current location and movement of people, wildlife, or in-animate objects. The key reason for this tracking is to be able to provide a timely help in emergency or unusual situations. Big drop in the cost of GPS[10] receivers has opened the possibility of cost-effective personal tracking systems. A basic GPS-based tracking system like automobile pilot system has a map installed. It receives signals from a satellite about its current location, and can show where the user is on the map. If the user wants someone else to know about his/her location, he/she needs a transmitter to transmit the location information. For example, in a child monitoring system, a child wears a transmitter, and can be tracked by the parents who have a receiver. The receiver receives location signal from the child either directly from the child's transmitter, or relayed via a base station and a backend network. General structure of current person tracking systems is a GPS receiver with a GSM, satellite, or RF transmitter[11], or the combination of them.

The main weakness of all these systems is that all of them are connection-oriented. This requirement limits their applicability under different situations. GSM transmitter has to be in the range of a base station to transmit. As a result, it cannot operate in most wilderness areas. While a satellite transmitter is the only viable solution in wilderness areas, it is typically expensive and cumbersome. Furthermore, a satellite transmitter requires line of sight to transmit to satellite, which make it inoperable in narrow canyons, large cities with skyscrapers, rain forests, or even when there is a roof or shelter above transmitter, e.g. in a car. An RF transmitter has a relatively smaller range of transmission. So, while an in-situ sensor is cheap as a single unit, it is expensive build a large network with them covering large winderness areas. In a highly mobile environment where sensors are carried by moving people, power efficient routing is nearly impossible. In wilderness area, building an adhoc sensor network organized by only hikers wearing a sensor is again nearly impossible.

In this paper, we propose a tracking system called Cenwits (A **C**onnection-less S**en**sor-Based Tracking System Using **Wit**nesse**s**). Cenwits is comprised of sensors worn by subjects (people, wild animals, or in-animate objects), access points (AP) that collect information from these sensors, GPS receivers, and location points (LP) that provide location information. A subject uses GPS receivers (when it can connect to a satellite) and LPs to determine its current location. The key idea of Cenwits is that it uses a concept of witnesses to convey subjects' movement and location information to the outside world. This averts a need for maintaining a connected network to transmit location information to the ouside world. In particular, there is no need for GSM transmitters, satellite transmitters, or an adhoc network of in-situ sensors.

There are three important advantages of Cenwits. First, Cenwits is a loosely-coupled system that does not require maintaining a connected network. As a result, this system can be deployed in remote wilderness areas, as well as in large urban areas with skyscrapers and other tall structures. Second, Cenwits is cost-effective. A subject only needs to wear light-weight and low-cost sensors that have GPS receivers. Since, there is no need for building an adhoc sensor network, there is no need to deploy these sensors in large numbers. Finally, Cenwits is power efficient. It is possible to control the times when the receivers and transmitters need to be on, thus manage power consumption regulation.

The rest of this paper is organized as follows. In Section II, we overview some of the recent projects and technologies related to movement and location tracking. In Section III, we describe the key ideas of Cenwits, and discuss important technical issues to build this system. To simplify our presentation, we will focus on a specific application of tracking lost/injured hikers in this section. However, Cenwits is applicable to a large number of varied applications, some of which have specific requirements. We discuss Cenwits in the context of these applications in Section III-D. In Section IV, we describe a preliminary prototype implementation, and conclude the paper in Section V.

II. Related Works and Technologies

A locationing system for adhoc sensor network using anchor sensors as reference to gain location information and spread it out to outer node was proposed in [8]. Most locationing systems in adhoc sensor networks are for benefiting geographic-aware routing. They don't fit well for our purposes. The well-known active badge system [14] lets a user carry a badge around. An infrared sensor in the room can detect the presence of the badge and determine the location and identification of the person. Active badge is a useful system for indoor environment where GPS doesn't work. Locationing using 802.11 devices is probably the cheapest solution for indoor position tracking and was proposed in [6]. Because of the popularity and low cost of 802.11 devices, there are several business solutions based on this technology[1].

A system that combines two mature technologies and is viable in suburban area where a user can see clear sky and has GSM cellular reception at the same time is also in the market[3]. This kind of device receives GPS signal from a satellite and locates itself, draws location on a map, and sends location information through GSM network to the others who are interested in the user's location. A very simple system that includes an RF transmitter and receiver[4] can alarm the holder of the corresponding receiver when transmitter is running out of range.

Personal Locater Beacons (PLB) has been used for avalanche rescuing for years. A skier carries an RF transmitter, which emits beacon periodically, so that the rescue team can find his/her location based the strength of the RF signal. Luxury version of PLB combines a GPS receiver and a COSPAS-SARSAT satellite transmitter that can transmit user's location in latitude and longitude to the rescue team whenever an accident happens[2]. Lifetch system developed recently at Poznan University of Technology uses GPS receiver board combined with a GSM/GPRS transmitter and an RF transmitter in one wireless sensor node called ICU (Intelligent Communication Unit). An ICU first tries to transmit its location to a control center through GSM/GPRS network. If that fails, it connects with other ICUs (adhoc network) to forward its location information until the information reaches an ICU that has GSM/GPRS reception. This ICU then transmits the location information of the original ICU via the GSM/GPRS network. Finally, a survey of location systems for ubiquitous computing is provided in [9]

Of all these systems, luxury PLB and Lifetch are designed for location tracking in wilderness areas. However, both of these systems require a connected network. Luxury PLB requires the user to transmit a signal to a satellite, while Lifetch requires connection to GSM/GPRS network. Luxury PLB transmits location information, only when an accident happens. However, if the user is buried in the snow or falls into a deep canyon, there is almost no chance that the signal can go through and be relayed to the rescue team. This is because satellite transmission needs line of sight. Furthermore, since there is no known history of user's location, it's not possible for the rescue team to infer the current location of the user. Another disadvantage of luxury PLB is that a satellite transmitter is very expensive, costing in the range of $750. Lifetch tries to transmit the location information by GSM/GPRS and adhoc sensor network that uses AODV as the routing protocol. However, having a cellular reception in remote areas in American national parks is unlikely. Furthermore, it is extremely unlikely that ICUs worn by hikers will be able to form an adhoc network in a large wilderness area. This is because the hikers are mobile, and it is very unlikely to have several ICUs placed dense enough to forward packets even on a very popular hike route. Also, GPS receivers usually update their location every 15 to 20 minutes. In downhill ski, this can means losing track of 3000 feet in elevation or 10 seconds in distance.

III. Cenwits

Cenwits is designed to address the limitations of systems such as luxury PLB and Lifetch. It is designed to provide hikers, skiers, and climbers who have their activities mainly in wilderness areas a much higher chance to convey their location to a control center. To simplify our description, we describe Cenwits in the context of locating lost/injured hikers in wilderness areas. Each hiker wears a sensor (MICA2 motes in our prototype) equipped with a GPS receiver and an RF transmitter. Each sensor is assigned a unique ID and it maintains its current location based on the signal received by its GPS receiver. It also emits beacons periodically. When any two sensors are in the range of one another, they record the presence of each other (witness information), and also exchange the witness information they recorded earlier. The key idea here is that if two sensors come with in range of each other at any time, they become each other's witnesses. Later on, if the hiker wearing one of these sensors is lost, the other sensor can convey the last known (witnessed) location of the lost hiker. Furthermore, by exchanging the information each sensor recorded earlier, the witness information can be propagated beyond a direct contact between two sensors.

To convey witness information to a control center or to a rescue team, access points need to be established at well-known locations that the hikers are expected to pass through, e.g. at the trail heads, trail ends, intersection of different trails, and so on. Whenever a sensor node comes is in the vicinity of an access point, all witness information stored in the sensor is dumped to the access point.

All access points are connected to a control center either via the Internet or via some other network. The control center downloads witness information dumped by various sensors from all the access points at various times. To track the movement and location of a hiker, all witness information of that hiker that is collected from various access points is processed.

An example of how Cenwits operates is illustrated in Figures 1, 2 and 3. First, hikers A and B are on two close

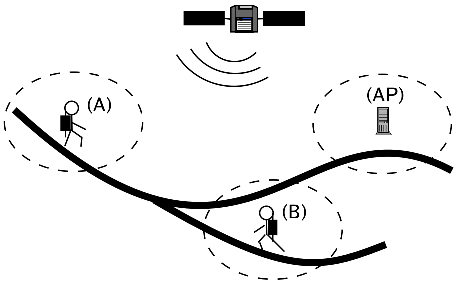

Fig. 1. Hiker A and Hiker B are are not in the range of each other

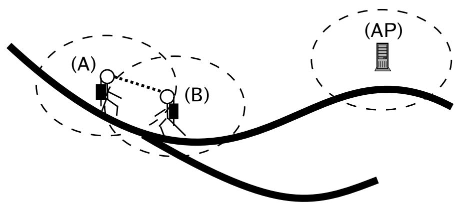

Fig. 2. Hiker A and Hiker B are in the range of each other. A records the presence of B and B records the presence of A. A and B become each other's witnesses.

trails, but out of range of each other (Figure 1). This is a very common scenario during a hike. For example, on a popular four-hours hike, a hiker might run into as many as 20 other hikers. This accounts for one encounter every 12 minutes on average. A slow hiker can go 1 mile (5,280 feet) per hour. Thus in 12 minutes a slow hiker can go as far as 1056 feet. This implies that if we were to put 20 hikers on a 4-hour, one-way hike evenly, the range of each sensor node should be atleast 1056 feet for them to communicate with one another continuously. The signal strength starts dropping rapidly for 2 Mica2 nodes to communicate with each other when they are 180 feet away, and is completely lost when they are 230 feet away from each other[5]. So, for the sensors to form a sensor network on a 4-hour hiking trail, there should be at least 120 hikers scattered evenly. Clearly, this is extremely unlikely. In fact, in a 4-hours, less-popular hiking trail, one might only run into say five other hikers.

Cenwits takes advantage of the fact that sensors can communicate with one another and record their presence. Given a walking speed of one mile per hour (88 feet per minute) and Mica2 range of about 150 feet for non-line-of-sight radio transmission, two hikers have about 150/88 = 1.7 minutes to discover the presence of each other and exchange their witness information. We therefore design our system to have each sensor emit a beacon every one-and-a-half minute. In Figure 2, hiker B's sensor emits a beacon when A is in range, this triggers A to exchange data with B. A communicates the following information to B: "My ID is A; I saw C at 1:23 PM at (39°49.3277655', 105°39.1126776'), I saw E at 3:09 PM at (40°49.2234879', 105°20.3290168')". B then replies with "My ID is B; I saw K at 11:20 AM at (39°51.4531655', 105°41.6776223')". In addition, A records "I saw B at 4:17 PM at (41°29.3177354', 105°04.9106211')" and B records "I saw A at 4:17 PM at (41°29.3177354', 105°04.9106211')".

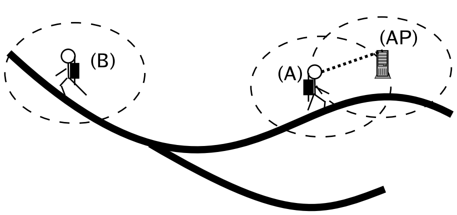

Fig. 3. Hiker A is in the range of an access point. It uploads its recorded witness information and clears its memory.

B goes on his way to overnight camping while A heads back to trail head where there is an AP which emits beacon every 5 seconds, so that no hiker misses this beacon. This is shown in Figure 3. A then dumps all the witness information it has collected to the access point.

A. Information Storage and Exchange Format

An important concern is that there is limited amount of memory available on motes (4 KB SDRAM memory, 128 KB flash memory, and 4-512 KB EEPROM). It is important to organize witness information efficiently. Our first observation is that we don't need to record everything we get from a GPS receiver. The circumference of the Earth is approximately 40,075 KM. If we use a 32-bit number to represent both longitude and latitude, the precision we get is 40,075,000/2^{32} = 0.0093 meter = 0.37 inches, which is much better than what we really need. In fact, a foot precision can be achieved by using only 27 bits. So, we need 54 bits for coordination. We can represent time in 17 bits to a second precision. Also, each node is assigned a unique ID when it enters a trail. This can be represented by a 16-bit number. Besides the time of encounter, we use another 9 bits to indicate how long ago the location reported by the sensor was recorded, e.g. A and B ran into each other at 4:17 PM and if A updated its location at 4:10 PM, the value of this field in A should be 7, indicating that A updated its location by GPS unit 9 minutes ago. A witness record stored in memory has the following format:

$$[-ID-][-Time-][-Coordination-][-TimeLag-]$$
$$[-16bits-][-17bits-][--54bits--][--9bits--]$$

Notice that we didn't reserve any memory for date. However, some hikes can span over multiple days. In that case, each node inserts a special encounter record in its own database when the date changes, i.e. at midnight, both A and B insert its own ID and then 17 consecutive 1s in Time field to indicate change of date. When A creates the witness packet to transmit to B, this day shift entry is included as well. The Time Lag field is important in inferring the location of a lost hiker. It is possible that a node received its location a 9 AM and lost sight of the satellite after that for 3 hours. Time Lag can be used to determine the range of possible current location of the hiker.

Finally, the size of witness information can get very large. This is because a node is storing not only the witness information it generates by a direct encounter, but also all witness information that the other node had recorded earlier. We can limit the size of this information based on available memory. For example, when A will tells B that it ran into C, D, and E earlier, B stores all this information in its witness information database. But later when B runs into K, B tells K that it ran into A and A ran into C, D, and E, K chooses to store only B ran into A. More experiments have to be done to decide an optimal threshold here.

B. Location Point and Location Inference

Although GPS receiver provides an accurate location information, it has it's limitation. Mainly in canyons and rainy forests, a GPS receiver does not work. When there is a heavy cloud cover, GPS users have experienced inaccuracy in the reported location as well. Unfortunately, a lot of hiking trails are in dense forests and canyons, and it's not that uncommon to rain after hikers start hiking. To address this, we propose to incorporate the idea of installing location points (LP). A location point can update a sensor node with its current location whenever the node is near that LP. Several LPs may be placed at some locations in a wilderness area where GPS receivers don't work. Note that while LPs allow a sensor node to determine its current location more accurately, they are not an essential requirement of Cenwits.

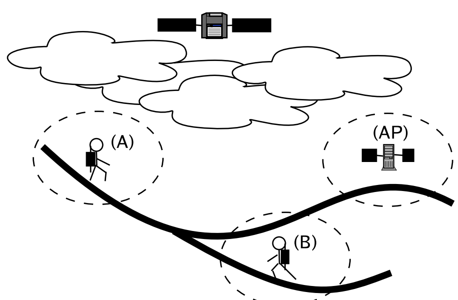

Fig. 4. GPS receiver not working correctly. Sensors then have to rely on LP to provide coordination

In Figure 4, B cannot get GPS reception due to bad weather. It then runs into A on the trail who doesn't have GPS reception either. Their sensors record the presence of each other. After 10 minutes A, is in range of an LP that provides an accurate location information to A. When A returns to trail head and uploads its data (Figure 5), the system can draw a circle centered at the LP from which A fetched location information for the range of encounter location of A and B. By Overlapping this circle with the trail map, two or three possible location of encounter can be inferred. Thus when a rescue is required, the possible location of B can be better inferred (Figures 6 and 7).

C. Beacon Time Period and Collision Prevention

An important advantage of using sensors for tracking purposes is that we can regulate the behavior of sensor node based on current conditions. For example, we mentioned that a beacon should emit a signal every 1.7 minute, given a hiking speed of 1 mile/hour. However, if a user is moving at 10

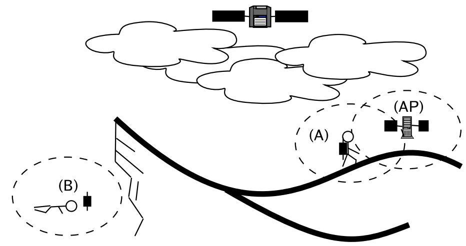

Fig. 5. A is back to trail head, It reports the time of encounter with B to AP, but no location information to AP

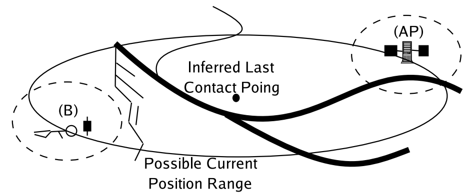

Fig. 6. B is still missing after sunset. Cenwits infers the last contact point and draws the circle of possible current locations based on average hiking speed

feet/sec, a beacon should be emitted every 10 seconds. If a user is not moving at all, a beacon can be emitted every 10 minutes. In the night, a sensor can be put into sleep to save the energy, when a user is not likely to move at all for a relatively long period of time. If a user is active for only eight hours in a day, we can put the sensor into sleep mode for the other 16 hours and thus save $2/3^{rd}$ of the energy. On the other hand, when a user wakes up and transmits/listens every minute, the highest speed allowed for two users moving towards each other on the same trail will be 100 feet/sec to communicate. In some downhill ski scenarios, this speed is indeed possible.

To conserve energy, we let a sensor wake up for 2 ms in every second. Because there are 2^{16} possible IDs, we divide the 2 ms time period into $1/2^{16}$ slices. Every sensor emits its beacon only in the slice corresponding to its ID in the 2 ms windows. Although the transmission time might be longer than $1/2^{16}$ms, as long as the beacons doesn't collide with each other, there is very little chance of any packets collision. Sensor nodes synchronize their clocks with an access point, whenever they are in the range of one.

D. Applications

In addition to the hiking application, Cenwits can be used in several other applications, e.g. skiing, climbing, wild life

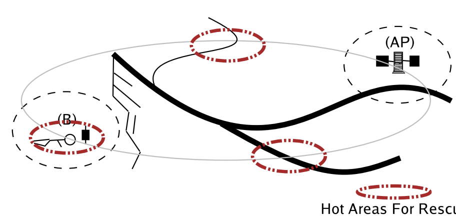

Fig. 7. Based on overlapping landscape, B might have hiked to wrong branch and fallen off a cliff. Hot rescue areas can thus be determined

monitoring, and person tracking. Given the fact that Cenwits is connectionless, it can take advantage of the existing cheap and mature technologies, and make tracking cheap and fairly accurate. Since Cenwits doesn't rely on keeping track of a sensor holder all time, but relies on maintaining witnesses, the system is relatively cheaper and widely applicable. For example, there are some dangerous cliffs in most ski resorts. But it is too expensive for a ski resort to deploy a connected wireless sensor network through out the mountain. With our system, we can deploy some sensors at the cliff boundaries. These boundary sensors emit beacons quite frequently, e.g. every second, and so can record presence of skiers who cross the boundary and fall off the cliff. Ski patrols can cruise the mountains every hour, and automatically query the boundary sensor when in range using PDAs. If a PDA shows that has been a skiers close to the boundary sensor, the ski patrol can use a long range walkie-talkie to query control center at base of resort to check the witness record of the skier after the recorded time of boundary sensor. If there is no witness record, there is a high chance that a rescue is needed.

In wildlife monitoring, a very popular method is to attach a GPS receiver on the animals. Data is collected either through a satellite transmitter, or wait until the GPS receiver brace falls off (a year or so) and then then search the GPS receiver. GPS transmitters are very expensive, e.g. the one used in geese tracking is $3,000 each. Also, it is not yet known if continuous radio signal is harmful to the birds. Furthermore, a GPS transmitter is quite bulky and uncomfortable, and as a result, birds always try to get rid of it. Using Cenwits, not only we can record the presence of wildlife, we can also record the habits of wild animals, e.g. lions might follow the migration of deers. We don't need bulky and expensive satellite transmitters, nor there is a need to wait for a year and search for the braces. Cenwits provides a very simple and cost-effective solution in this case. Also, access poits can be strategically located, e.g. near a water source, to increase our chances of collecting up-to-date data.

In large cities, Cenwits can be used to complement GPS, since GPS doesn't work indoor and near skyscrapers. If a person A is reported missing, and from the witness records we find that his last contacts were C and D, we can trace an approximate location quickly and quite efficiently.

IV. Prototype Implementation

We've implemented a preliminary prototype of Cenwits on Mica2 running Mantis OS[7]. Listen code and transmission code are run by parallel threads. When there is no activity in the system, the CPU is put in power-safe mode and the threads are put in ready queue after the sleeping time has elapsed. Current implementation does not support time critical applications.

Another challenge we ran into is how to divide 2 ms into 2^{16} slices. This requires $1/2^{19}$ sec time precision, the time precision provided is only $1/2^{6}$ sec. So, in the current implementation, we divide 2 ms into 2000 slices, and it's enough for now. We are still working on ways to get a better precision here.

There is 4 KB flash memory available for applications. Since, each witness record is 10 bytes long, we can easily save 400 records. We experimented with a very simple application comprised of five sensors that emit a beacon every five seconds and listen every minute. Data collected at the end of a day showed witness records successfully.

V. Discussion and Future Work

This paper presents a new tracking system called Cenwits that has several advantages over the current tracking systems. These include no need for a connected network, cost-effectiveness, and power efficiency. The system based on the idea of witnesses is quite intuitive and straight forward. The paper describe several high-level, technical details of the system. Future work includes developing a more mature prototype, addressing important issues such as security, reliability and privacy, and experimenting with the system in a realistic environment.

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