A Low-Power Multi-Radio Wireless Network for Mobile Asset Tracking

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Abstract—**This paper proposes a hierarchical wireless system for real-time tracking of moving assets. There are multiple layers of wirelessly connected assets that need to be tracked. The small items, such as bottles, packed in a box are monitored by a sensor module contained within each box. All boxes shipped in a cargo truck form an ad hoc network that adapts to the battery level and link quality. A small subset of boxes are dynamically selected to report sensor information to a backend server. A wireless networking protocol is proposed to minimize the power consumption based on available energy and wireless link conditions in the distributed hierarchical system. The system is validated by simulation and prototype implementations.**

Keywords-asset tracking; low-power; sensor network

I. INTRODUCTION

Asset tracking has become increasingly important to multiple parties, whether it be a company keeping track of inventory, or a delivery provider keeping track of packages being transported through its delivery network. Customers are adding more quality of service requirements, for example, real-time tracking of moving targets, keeping track of every single item in a box, theft prevention for expensive packages, security and privacy, and so on. In addition to tracking, extra information such as temperature and humidity of the tracked items may be requested. Shippers, carriers, recipients, and other parties often wish to know the location, condition, and integrity of shipments before, during, and after transport to satisfy quality control goals, meet regulatory requirements, and optimize business processes. On the other hand, customers are very sensitive to the cost.

To meet the above quality of service requirements, a highly organized and low power wireless ad hoc network for asset tracking is necessary. Effective management and autonomous operation of such networks allows for lower cost, reduced delivery time, and enhanced customer service. Recent advances of wireless technology make such a wireless network possible. However, this requires a hierarchical system that takes care of both item-level data retrieval and sensing and long-range remote monitoring. Instead of achieving a theoretically global optimal solution, a highly practical, localized, and cost-effective solution is the key to the success of commercializing such a system.

Given the above market requirements and technical challenges, this paper proposes a multi-radio mobile asset tracking system that provides near real-time tracking of large amount of assets at multiple levels. One of the major system design goals is to lower the power consumption of every tracking device, which will eventually help extend their life time and reduce overall cost. The rest of the paper is organized as follows. Next section provides background information and reviews related work. The system architecture is described in Section III. The technical details of the collaborative protocol are explained in Section IV. Section V presents results, and Section VI concludes the paper.

II. RELATED WORK

Table I summarizes the current commercial units in use for mobile asset tracking.

TABLE I. COMMERCIAL MOBILE ASSET TRACKING UNITS

	LogiBoxx	**inGeo F1**	**inGeo F2**	**PT200**	**SenseAware**
WWAN	GPRS	CDMA	CDMA	CDMA	GPRS
Sensors		Motion	Motion	Motion, Light, Shock, Temp	Motion, Temp, Light, Humidity
RFID	Active, passive RFID				
GPS	Yes	Yes	Yes	Yes	Yes
Misc			Zigbee		

LogiBoxx [1] is an integrated GPS/RFID unit. An integrated reader in the cargo reads proprietary tags or seals within a specified area. Route control information can be monitored using geo fences and alerts can be sent if a preprogrammed route is ignored. The inGeo [2] F1 is an integrated GPS/CDMA device with accelerometer. The inGeo F2 device adds an optional Zigbee radio. Geo fences can also be created and alerts can be sent when they are breached. The accelerometer can be used to monitor shock and motion. The SenseAware [3] is an integrated GPS/GPRS device with additional integrated temperature, light, and humidity sensors. The Sendum PT200 device [4] is another integrated GPS/CDMA unit with an optional multi-sensor accessory which provides motion, light, shock, temperature information. There has been a general trend in the commercial units to provide detailed information not only on the cargo, but also at the item and box level.

Power saving for sensor networks has been extensively studied [5-12], but most of them consider single-radio sensor devices that form a local network. For the approach proposed

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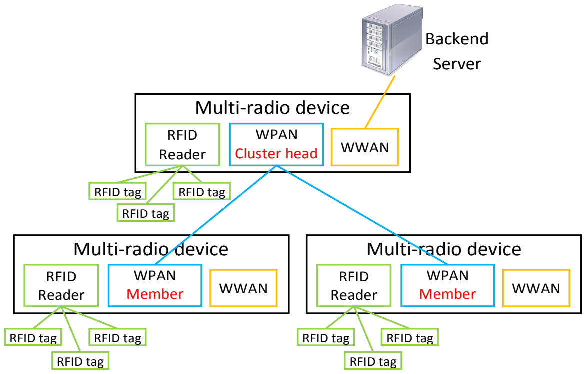

Figure 1. System architecture

in this paper, the local sensor devices only communicate with neighbors with little information exchange, while helping to save power of another long distance radio that provides mobile remote monitoring. Clustering in wireless ad hoc networks is also an active research topic (see [6, 7] and references therein). Many algorithms have been studied for efficient clustering in terms of reducing convergence time and minimizing number of clusters. However, many of the protocols involve significant amount of computation and communication overhead that impacts their practicability in a low-cost tracking device considered in this paper. The adaptive clustering protocol suggested in this paper reduces such overheads by making the algorithm autonomous in each device without exchanging any control information with other devices. There have been many practical deployments of multi-radio and hierarchical wireless sensing systems [8, 9]. Some deployments such as [8] typically address fixed/mobile sensors with typically fixed gateway nodes. Other deployments such as [9] address fixed/mobile sensors with mobile gateways, where gateway nodes are not necessarily within wireless proximity of each other. Our work addresses the problem of mobile gateway nodes with differential connectivity to different wireless networks that dynamically impacts the selection of the gateway nodes in the network based on wireless link conditions in Wireless Wide Area Network (WWAN), where such gateway nodes have relatively fixed connectivity to a hierarchical sensor network, and where such gateway nodes are within wireless proximity of each other.

III. System Architecture

The proposed hierarchical system architecture is illustrated in Fig. 1. Each box is equipped with a multi-radio device. Multiple boxes are packed in a container such as a cargo truck. Each box is filled with multiple small items that may need to be tracked separately. The WWAN radio is used for long distance data communication to the backend server. However, it typically consumes much higher power than short range wireless radios, such as ZigBee and RFID. So it is not practical to have each device directly use its WWAN radio to report status. Instead, a Wireless Personal Area Network (WPAN) based sensor network handling most of data information exchange locally is more desirable, so that the overall power consumption in the distributed system can be significantly reduced. The description for each radio and its functions can be found below.

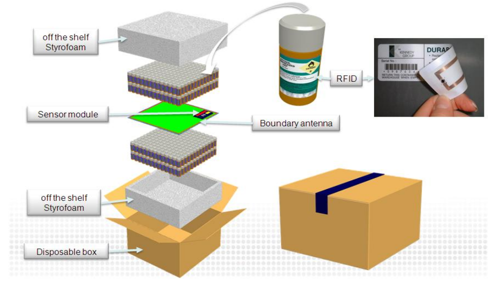

Figure 2. Box, items, and antenna

A. RFID

There can be multiple items in a box that contains a multi-radio device. Each of the items has a passive RFID tag attached to it to report its presence and other information to the multi-radio device's RFID reader which periodically polls such data from all tags. A standard shipping box is 16 inches long, 16 inches wide, 16 inch deep. But a typical RFID reader can only communicate with tags within 4 inch of distance. In order to ensure that all tags in the box are covered, an antenna that is designed to extend along the perimeter of the box is included, as shown in Fig. 2.

B. WPAN

The WPAN module is responsible for short range wireless communications between the multi-radio devices (one in each box) to facilitate communications amongst the boxes in the container. By keeping most of the data exchange amongst local devices, only a small amount of devices need to be selected as representatives that send the collected data from their neighbors to the backend server. Each WPAN radio inside a device acts in one of the following two roles:

- **Cluster head**. A small subset of devices are selected as cluster heads. Each cluster head periodically collects data from all members in its cluster and sends its data to the backend server through its WWAN module. A cluster head decides if a new device is allowed to join its cluster. It may quit being a cluster head under different conditions such as when the remaining battery energy level is low or if the WWAN link conditions are poor, or to implement a distributed policy that allows different devices to operate as cluster heads at different times. A device can choose to be a cluster head when WWAN link conditions are good, or if battery energy level is high, or based on a distributed policy for cluster head determination.
- **Member**. Most devices are members. Each member must be associated with a cluster head. It sleeps most of the time to save power. It only wakes up to report its data to its own cluster head periodically. Its WWAN module is always turned off.

A simple cluster management scheme is needed. It does not have to be globally optimal in terms of minimizing the number of cluster heads or overall power consumption because such a distributed management protocol that would seek global optimality could itself consume significant amount of

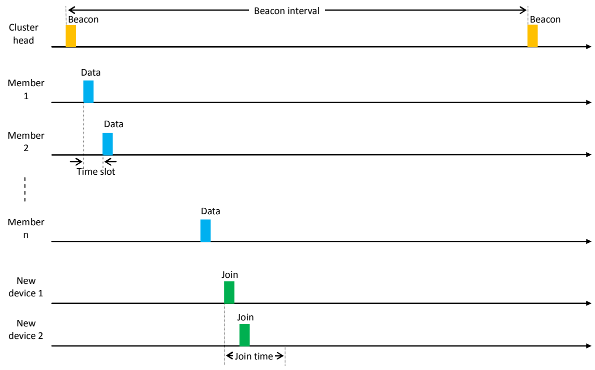

Figure 3. Timing in a cluster

computation and communication resources. For the same reason, complicated multi-hop routing and centralized algorithms are not practical as well. In the next section, a simple and energy-efficient protocol will be detailed.

C. WWAN

The WWAN module in the multi-radio device is only turned on by cluster heads and is employed for communication with a remote backend server in the long range mobile environment for the WWAN. The WWAN module can support multiple WWAN technologies, so that at any given time, each multi-radio device could be connected to a different WWAN technology/network/channel, such that each device could experience a different link condition with respect to the WWAN that it is connected to. This provides diversity of connectivity to WWANs, providing fault tolerance of connectivity by exploiting multiple available WWANs through different devices concurrently. At any given time, the devices with the best WWAN connectivity, based on cost of connectivity, network load, or WWAN link quality, can be chosen to be cluster heads.

IV. Low-Power Collaborative Scheme

This section focuses on the collaborative scheme in WPAN among all devices in a container. The beacon protocol is introduced first, followed by cluster head selection protocol.

A. Beaconing

Due to the large number of devices and the short communication distance of WPAN, one cluster head usually is not enough to cover all other devices. Therefore, multiple cluster heads may be selected to collectively enable wireless wide area access to the distributed set of devices. A cluster head and all its members are synchronized by the beacons sent by the cluster head periodically. The basic timing within a cluster is illustrated in Fig. 3, which will be explained in more details below.

A cluster head periodically sends a beacon, which is used to manage existing members in its cluster, as well as to inform new devices regarding the availability of its cluster. A beacon packet format is specified in Fig. 4. The list of members provides the address of all existing members that belong to this cluster. The Beacon Interval field indicates the time between

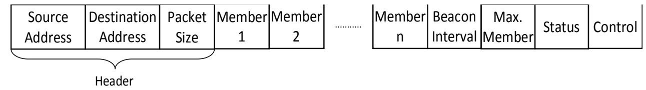

Figure 4. Beacon packet format

two consecutive beacons. The Maximum Member field specifies the upper-bound of the number of members supported in this cluster. The Status field informs the neighbors that this is either a working cluster head or that it is quitting cluster head operations as explained in following sections. The Control field includes control information for members whether they need to report their sensor data following the beacon.

A cluster head needs to collect data from all its members, either periodically or triggered by certain events. Each member may go to sleep mode when it is idle. Once a member receives the beacon from its cluster head, it learns if it needs to report data according to the Control field in the beacon. If yes, the member will send a Data packet. Each member will have its own specific time slot after the beacon, which is in the same order as the member that is listed in the beacon. The Data packet format is specified in Fig. 5. The Slot Number field identifies the time slot used by this member to send its Data packet. The IDs contain the item identification information collected by the RFID reader. Sensor Data field reports sensor data information, such as temperature, humidity, etc. Control field includes such control information as battery level, link quality, volunteer to be cluster head, etc. The optional Neighbor List may also be included.

B. Cluster Head Selection

Before a device decides whether it has to start its own cluster or join an existing cluster, it needs to scan the channel for at least one beacon interval, in order to gather information from neighbor devices. If no beacon or other packet is detected during scanning, the device itself will become a cluster head and start sending its own beacon immediately.

If an existing cluster head's beacon is received during scanning, the new device will send a Join control packet to the cluster head during the join time, which is after beacon and all Data packets are transmitted. The exact transmission time of each Join packet is randomized in order to avoid collisions among multiple Join packets.

When there are multiple beacons, Data, or Join packets received during scanning, the new device has to select one of the clusters to join, without interfering all the other neighboring clusters. Basically, when the scanning device receives a beacon from another cluster head at time T_0, it implies that, following this beacon, that cluster head will also receive Data packets from all its members and potential Join packets from new devices joining that cluster. Assuming that the transmission time for a beacon is T_{beacon}, that cluster head has n members, each takes a time slot of length T_{slot}, and join time is T_{join}, then

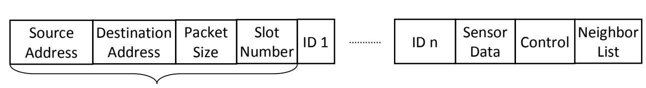

Figure 5. Data packet format

that cluster will occupy the channel during time interval:

$$[T_0 - T_{\text{beacon}},\quad T_0 + n * T_{\text{slot}} + T_{\text{join}}], \tag{1}$$

repeatedly in every beacon interval. Therefore, this new device is not allowed to transmit or receive during the same time.

When the scanning device receives a Data packet from a member X in another cluster at time T_1, it implies that X has received a beacon from its cluster head before. Specifically, assuming X is in time slot i and the transmission time for its Data is T_{data}, it should have received a beacon sent at time $T_1 - (i - 1) * T_{\text{slot}} - T_{\text{beacon}}$. Therefore, the new device should not transmit or receive during time interval:

$$[T_1 - (i - 1) * T_{\text{slot}} - T_{\text{beacon}},\ T_1 - T_{\text{data}} + T_{\text{slot}}], \tag{2}$$

repeatedly in every beacon interval.

Therefore, at the end of scanning, the new device learns that there are multiple time intervals when the channel is already occupied. It runs following algorithm to decide which cluster to join.

1. Sort all the time intervals in the increasing order of the starting time.
2. Merge all adjacent intervals if they are overlapping until none of the remaining intervals overlap.
3. Among remaining time intervals, find those that are not affected by any merging and are only detected due to a received beacon from a cluster head that still has opening for new members to join. Amongst these candidate intervals, by selecting the interval with the longest gap between its end time and its immediate next interval's starting time, the corresponding cluster will be selected as the one to join.
4. If no such time interval is found in last step, then it implies that there is no cluster head in the neighborhood that is interference-free and ready to accept new members. Therefore, this scanning device will start a new cluster as a cluster head. To avoid interfering any existing neighbors, this new cluster should find an available time duration that resides in one of the gaps between the above found time intervals. A common rule is to find the largest gap.
5. Once the scanning device makes the decision of either joining an existing cluster or starting a new cluster, it has to wait until its available time duration to send a Join packet or a beacon, respectively. Until then, it has to continue scanning the channel. If any updated information is collected during this scanning period, then it has to go to step 1 again.

Obviously, a cluster head consumes much more power than its members. To make power consumption more evenly distributed amongst all devices in a container, each cluster head should quit and resume cluster head operations for time intervals during which other devices could operate as cluster heads. The time interval during which a cluster head discontinues cluster head operations is determined by one or more factors below:

- The battery level of current cluster head has dropped below certain threshold.
- The link quality is getting degraded between this cluster head and the server.
- A certain amount of time has passed since providing cluster head operations.
- Whether other devices have connectivity to WWAN, and the quality of such wireless links.

Existing cluster head selection algorithms try to find the optimal number of cluster heads by utilizing more information such as network topology, as well as more communication overhead to exchange such information among devices. This makes the existing algorithms impractical to a real system that requires low power, simple implementation, and robust operation. Furthermore, by using existing algorithms, a certain subset of devices may always be selected as the optimal selection of cluster heads, which makes it hard to change dynamically. Below is a simple distributed and localized protocol to select and change new cluster heads.

1. When a cluster head decides to quit being a cluster head, it informs its members by setting the Status field in beacon to 'quitting'.
2. After sending/receiving a beacon with Status field set to 'quitting', both the cluster head and its members start scanning in order to find another cluster to join or start a new cluster. Each device may choose a random duration of time to scan in order to avoid conflictions among them. The old cluster head will scan the longest time in order to get a better chance to find a new cluster head to join.
3. If more optional control information is available, the old cluster head may provide additional directions to its members. For example, if the old cluster head has the information of battery level of all its members, it may use it to give preference to members with higher battery level by re-ordering the member list in its last beacon, in which the member with higher battery level is listed earlier. The member listed earlier will spend shorter time scanning than the member listed later. By doing this, members with higher battery level will complete scanning earlier and have a better chance to become a new cluster head.

V. RESULTS

A prototype is developed to validate the proposed system architecture. The WWAN, WPAN, and RFID components of the system are implemented by MSM cellular radio, Jennic IEEE 802.15.4 radio, and NXP RFID, respectively.

TABLE II. POWER CONSUMPTION NUMBERS

Power Consumption	WWAN	WPAN	RFID
Tx (mA)	142	15	100
Rx (mA)	142	17	100
Sleep (mA)	0.6	0.00425	0
Turn on (mA)	100 for 4 sec.	0	0

Based on measurements from the prototype devices located in a truck cargo, Table II shows the power consumption numbers are used for further studies. Extensive simulation has been done to study the system performance in various scenarios when the number of devices N is between 100 and 1000. It is based on an event-driven wireless simulator [13]. Without loss of generality, following parameters are used in the simulation: All devices are randomly distributed in a 3-dimentional container with X = 10 m, Y = 10 m, and Z = 10 m. Default transmission range R = 3 m. Beacon interval is between 1 and 60 minutes. Each scenario is simulated for 24 hours.

Table III shows the average power consumption of each device when network size N = 1000. For non-cluster case, since every device reports its data through WWAN separately, the overall power is dominated by WWAN. By using proposed local dynamic cluster selection, the total power consumption is greatly reduced, which implies longer battery life.

TABLE III. POWER CONSUMPTION RESULTS

Power Consumption	Total	WWAN	WPAN	RFID
No cluster (mAh)	27.4	24.0	0	0.3
Dynamic cluster (mAh)	6.5	1.2	1.8	0.5

Fig. 6 shows the overall power consumption (max, average, and min) with dynamic cluster selection for different network sizes. Due to time-varying WWAN link conditions, different nodes can be connected to different WWAN networks, so that at any given time some nodes can have better link conditions than others. As link conditions vary, nodes with better quality links consumes less power and has a higher probability to become cluster heads. Due to the dynamic nature of wireless channel, different nodes are able to take on the role of a cluster head. Utilization of better wireless links results in overall reduced energy consumption in the system. Fig. 7 displays the power breakdown of different radios.

Fig. 8 is a snapshot of network topology in the middle of operation when some devices (circles) quit being cluster heads (black dots) and are trying to find a new cluster.

VI. CONCLUSION

Mobile asset tracking is an emerging market that depends on technology advances in both short range and long distance wireless communications. In this paper, a multi-radio hierarchical wireless tracking system is presented to handle both item-level sensing and cargo-level remote monitoring. A collaborative scheme is proposed to exchange most of the data inside the cargo and dynamically select a subset of devices to report data to the server. It shows the benefits of dynamic cluster selection under varying WWAN link conditions for mobile asset tracking systems. Prototype and simulation results are presented to demonstrate the practicability and performance of the proposed solution. Based on this study, we are working on reliable RFID coverage within each box, as well reducing the power consumption during radio idling.

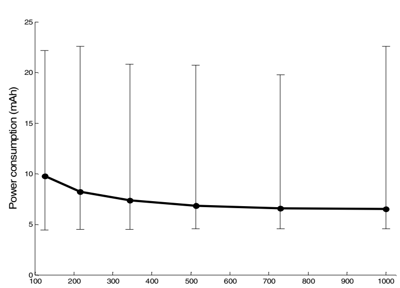

Figure 6. Total power consumption with dynamic cluster selection

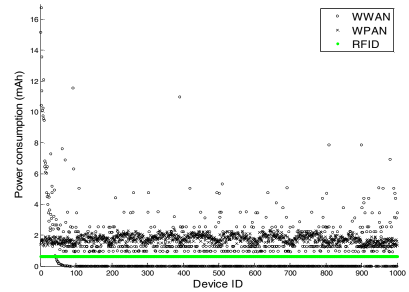

Figure 7. Power consumption breakdown

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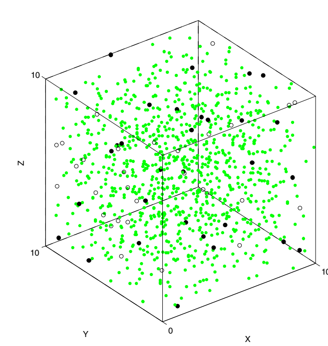

Figure 8. Network topology during dynamic cluster head selection