An Ultra Wide Band (UWB) based Sensor Network for Civil Infrastructure Health Monitoring

Vipin Mehta, Magda El Zarki
Dept. of CS, UC, Irvine
{vipinm, elzarki}@uci.edu

Abstract— **Communicating with sensors has long been limited either to wired connections or to proprietary wireless communication protocols. Using a ubiquitous and inexpensive wireless communication technology to create Sensor Networks will accelerate the extensive deployment of sensor technology. Ultra Wide Band (UWB), an emerging, worldwide standard for low power, high throughput local wireless communication is a viable choice for sensor networks because of its inherent support for some of the important requirements - throughput governed adaptive communication range, low power, low cost and small form factor. In this work in progress paper we outline an approach, centered on the UWB technology, to support a sensor network composed of fixed wireless sensors for health monitoring of highways, bridges and other civil infrastructures. We present a topology formation and a media access control scheme coupled with a mechanism for data aggregation to collect the sensor data.**

I. INTRODUCTION

Recent efforts in the area of characterizing the UWB propagation characteristics for both indoor and outdoor channels, antenna design, low complexity transceiver architectures and signal processing is expected to boost the use of this technology resulting in cheap and portable devices with integrated sensing, computing and communication capabilities. A network of devices based on this technology can be used for automated information gathering and distributed micro sensing in many civil applications such as home energy management, civil infrastructure health monitoring, etc. For the latter application in particular, Civil Engineers need the flexibility to place sensors in locations that are critical for health monitoring but that may not be convenient for existing wiring schemes. In many situations it is difficult to rewire the existing infrastructure. Many of these scenarios thus call for wireless sensor networks as opposed to wired ones. Wireless networks can be much more cost and time effective because they are easier to deploy especially in remote locations. In some application scenarios, a wireless solution can vastly reduce the monitoring installation cost, where the cabling alone generally constitutes 30-45% of the total cost.

In this paper we address the problem of designing a sensor network, composed of fixed wireless sensors, for deployment in existing civil infrastructures such as bridges, and highways, to monitor stress, vibration, temperature, humidity, etc. The scope of this work is also equally applicable to the concept of smart spaces which typically require high throughput. Although the sensors are fixed, they are deployed in an ad hoc fashion (dependent upon need and accessibility) and sensors can die and be replaced, or new ones added, at any time. The protocol has been specifically designed to reduce this deployment cost by forcing all the nodes, either close or distant from the data collection hub, to be drained off their energy at approxiamately the same time. Given current wireless networking technologies, the specific needs of such sensor networks and the desire for a near term deployment, we propose a solution based on Ultra Wide Band technology. In section 2 we introduce Ultra Wide Band technology and address the suitability of using it for this particular application. In section 3, we discuss our proposed solution. Section 4 presents some ideas on the physical system design and the simulation setup being used to evaluate the performance of the proposed protocol. We conclude in section 5 with some directions we are planning to explore.

II. ULTRA WIDE BAND TECHNOLOGY

The term, Ultra Wide Band is often referred to in several other ways: impulse, carrier-free, baseband, time domain, non-sinusoidal, orthogonal function and large-relative-bandwidth radio/radar signals. Here, we use the term "UWB" to include all of these. The UWB approach to radar and communications is, if not a shift in paradigm, at least a shift in emphasis with respect to the use of the available time-bandwidth-power product. It allows for high bandwidth with low SNR signal generation at the expense of very short pulses in the time domain. An ultra wide band signal is any electromagnetic signal whose instantaneous fractional bandwidth ($\frac{2(f_H - f_L)}{(f_H + f_L)}$) is greater than 0.25 w.r.t. the center frequency. Most narrowband systems carry information, also called the baseband signal, as a modulation of a much higher carrier frequency signal. The important distinction is that the UWB wave form combines the carrier and baseband signal. There is also a distinct difference between spread spectrum and ultra wideband systems. Spread spectrum systems have a transmitted signal that is spread over a frequency band much wider than the minimum bandwidth required to transmit the information being sent. A spread spectrum system takes a baseband signal with a bandwidth of only a few kilohertz and distributes it over a larger bandwidth. While spread system signals have a wide bandwidth w.r.t. other signals, they generally do not fit the UWB definition as their fractional bandwidth is well below 25%.

Several technologies like Bluetooth, IEEE 802.15.4, Berkeley motes, etc have been explored for the realization of sensor networks. UWB appears competitive in this field and could be exploited as a promising and flexible transmission technology. Most of the UWB systems studied in literature have been based on signals using narrow time domain impulses transmitted with the aid of time-hopping spread-spectrum techniques or position modulation. Often referred to as Impulse Radio (IR), the signals are transmitted with a bandwidth much larger than the data modulation bandwidth and thus with a reduced power spectral density. Such high bandwidth ($\sim$ GHz) allows the multipath to be resolvable down to path differential delays on the order of a foot or less. This significantly reduces the multipath fading and reduces the corresponding margins in link budgets. Low spectral density ensures that it does not interfere with narrow band systems operating in dedicated bands. UWB also allows for reconfiguration of throughput vs range, due to availability of number of transmission parameters, which can be tuned to better match the requirements of data aggregation in a sensor network. As far as the sensor nodes hardware architecture is concerned, it is relatively cheaper as the structure of the receiver is very simple due to the absence of a carrier.

III. MEDIA ACCESS CONTROL AND DATA AGGREGATION

We propose a topology formation scheme based on a time division multiplexing access mechanism. The network consists of a number of nodes capable of sensing, processing and communicating the data. The sensor data is collected by a special data collecting node, called the 'sink', that is responsible for controlling the dynamics of this network. The sink is assumed to have access to unlimited amount of energy and computational power as compared to rest of the sensor nodes which enables it to synchronize their access to the channel and also execute a complex optimization algorithm, governed by a system of equations, to compute their routing and transmission schedules. The desired objective of a large sensor network is that after the nodes are deployed, they should be able to organize themselves automatically into an ad-hoc network and start sensing, collecting and forwarding the data. Although each of the nodes can have a device specific unique identification based on a 32 bit or a 48 bit scheme, the protocol has a provision for the auto generation of a unique ID which is optimized for the use in the channel access and routing phases. The nodes are responsible for collecting the information about their neighbors and communicating it to the sink. The sink is responsible for collating all this information and using it to decide upon a schedule and routing path for each one of the nodes. The entire approach is a hybrid of a distributed and a centralized solution as the neighborhood information is gathered through the former while the access to the channel is decided upon using the latter. This allows us to reap the benefits of uncoordinated access in the beginning while coverging to an optimal solution in terms of bandwidth allocation and routing of traffic after the schedule is computed. Since most of the processing takes place at the sink, it alleviates the need for the sensor nodes to be endowed with high computational power. The protocol can be divided into two phases, namely:

- Topology Formation
- Data Aggregation

A. Topology Formation

The Topology formation phase is characterized by each node having to undergo the following steps in sequence:

- Assigning unique identities to the nodes.
- Discovering one hop neighbors.
- Performing ranging operation to get distance estimates to the sink and immediate neighbors.

Each of these steps is interspersed with a direct transmission from the nodes to the sink to communicate the results of the previous step. The topology formation phase starts with the sink node broadcasting a synchronization signal through the diameter of the network. This signal, called Reference Broadcast Signal (RBS) or 'beacon', acts as a reference pulse for all the other nodes in the network indicating the start of a beacon interval.

Starting with the *identification assigning* step each node picks a random number from a sequence, the range or possible set of values for which is specified in the beacon packet transmission from sink to node and uses it as its identification or 'signature' from then onwards. In case two or more nodes happen to chose the same signature, the collision is detetcted by the sink in the subsequent beacon intervals and resolved as described later in the section. Instead of using the conventional carrier sensing (CS) approach, the nodes use a time offset multiplexing (TOM) scheme to arbitrate access to the channel by using their signature as a delay parameter (slot number) to transmit a packet after they detect the RBS. All nodes start by advertising their identities directly to the sink. The amount of power required for this can be estimated based on the Received Signal Strength Indication (RSSI) value of the RBS at the node and the amount of power at the transmitter with which the sink sent the RBS. The latter may either be known to be of some fixed value or it may be included by the sink in the beacon packet. The proportionality constant (slot duration) is such that the minimum temporal difference between any two adjacent numbers of the sequence is

- greater than atleast twice the average time it takes for a signal to propagate through the network. This comes directly from the fact that if there are two nodes one lying the closest possible distance to the sink and the other lying the maximum possible distance from the sink, then in order for the sink to distinctly receive the signatures from these two nodes, in the case when the latter have selected two adjacent random numbers in the sequence, they should have enough difference between their respective reception timings at the sink to compensate for the round trip propagation time between the two nodes.
- takes in to account the transmission time of the advertising packet

The optimization problem of maximizing the network lifetime, described in the next subsection, requires the knowledge of the distance between the nodes and the sink. Distance information is also collected during the ID finding step. The sink records the time at which it sends the beacon and the time at which it detects the response from a node. Since the difference between the two only depends on the propagation delay and the signature of the node, it allows the beacon to get an estimate of the propagation delay and hence the distance. In subsequent beacon packets following the current one, the sink transmits the IDs of the all the nodes from which it has received signature information. This allows the nodes to verify if their signatures were succesfully registered with the sink and therefore stop advertising. If there is a collision because two or more of the nodes happen to pick the same random number, the sink receives a corrupted transmission as the CRC check used to verify the integrity of the packet will fail. The contents of the packets of the colliding nodes are made unique (and hence the uniqueness of the CRC) to avoid multiple such transmissions to be interpreted as multipath signal components by a RAKE receiver. These nodes would thus not be able to find their IDs in subsequent beacon packet transmissions forcing them to pick another number from the sequence and not present in the IDs already detected. The sink decides to terminate this phase once it does not hear from any node during a beacon interval and advertises it to the nodes in its next beacon transmission. The beacon interval is large enough (contains enough slots) to accomodate the entire range of random numbers. There is an interesting tradeoff that we intend to explore here of that of the range of random numbers to chose from and the number of cycles it takes to converge. Because the smaller the range, the shorter the time interval between successive beacons. However, it will take a larger number of cycles to converge to a unique set of IDs for all the nodes.

During the *neighbor discovery* step, each node advertises its ID to all its one hop neighbors following the TOM mechanism. The amount of power to be used can be either estimated by the sink based on its perception of the node density (and hence the average distance between two nodes) or it can be modelled on the lines of Swarm intelligence [5]. Once a node gets this distance info, it adjusts its power accordingly and advertises its identification. Note that the number of advertisements a node receives is an indication of now many nodes it is able to reach thus giving it some sort of degree information. It is assumed that the search for the appropriate power to use for one hop neighbors converges in a fixed predetermined number of cycles. The advantage of encoding the signature in the advertising packet is that it allows the nodes to calculate the relative clock offsets with their neighbors which is equal to the difference between the time a particular advertisement was received and the epoch boundary corresponding to the signature. Once each node gets to decide what its one hop neighbors are, they communicate this information using the TOM mechanism to the sink. The sink needs to know the one hop neighbors of all the nodes to compute the routes and transmission schedules. This information also allows the sink to include in the subsequent beacon packet, the maximum number of neighbors for any node which determines the number of cycles the next step of range estimation would have.

At the end of the signature and neighbor determination phase and starting with the next RBS, each node emits a *ranging* pulse for each one of its one hop neighbors using TOM. This ensures that the node itself gets such a request from all its one hop neighbors at non-overlapping instants of time and that none of the transmissions overlap thus keeping intact the half duplex semantics of the transceiver. A node getting a request replies to it after waiting for one full beacon interval. Each of the nodes then calculate the two way propagation delay by subtracting the amount of time equal to a beacon interval from the total time elapsed between a request ranging pulse and its response. The nodes transmit the distance information directly to the sink after the number of cycles, specified in the beacon packet, have elapsed. The sink then starts the schedule determination phase wherein it decides the schedule each node is meant to follow and the relay node it will use for data forwarding. This is framed as an optimization problem through which the sink tries to maximize the network lifetime. In the conventional approaches, either a group of nodes relay their traffic to a candidate node which then transmits it to the sink on their behalf or the nodes transmit their traffic hop by hop to the sink. While in the former the nodes that are far from the sink lose their energy quickly as compared to the ones that are closer to sink, in the latter, the opposite thing happens since the nodes closer to the sink spend more energy routing the traffic of their predecessors. In the proposed approach, a node uses its one hop neighbor as a relay node only to the point till the routing data does not dominate the actual data generated by the relay node. It transmits the data to the sink directly as soon as possible to avoid depleting the energy of the nodes closer to the sink. Consider the system of ‘n’ nodes as shown in Figure 1 with the amount of traffic, ‘λ’ they generate per unit time.

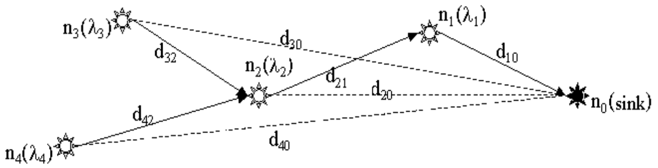

Fig. 1. A System of nodes in a sensor network

The entire system’s energy consumption can be modelled through the following set of equations, where the first term in the energy relation captures the energy consumed during transmission while the second and third terms reflect the reception and switching energy respectively. The energy consumed by a receiver can be considered to be proportional to the amount of data being received by the node. Thus:

$$E_i = \begin{cases} (k_1 \acute{\lambda}_i \{d_{i0}^{\alpha} t_i + d_{i\Re(i)}^{\alpha}(1-t_i)\} + k_2 \acute{\lambda}_i + E_s)_{\forall i, \Re(i) \neq n_0} \\ (k_1 \acute{\lambda}_i \{d_{i0}^{\alpha}\} + k_2 \acute{\lambda}_i + E_s)_{\forall i, \Re(i) = n_0} \end{cases} \quad (1)$$

where, node $\Re(i)$ is the relay node for node n_i and $\Re^{-1}(i)$ constitutes a set of all nodes for which node n_i is the relay node. The path loss exponent, 'α' can assume values between 2 and 4 and 't_i' is the fraction of time for which the node should relay the traffic directly to the sink.

$$\acute{\lambda}_i = \begin{cases} \lambda_i + \sum_{j\in\Re^{-1}(i)} \lambda_j (1-t_j)_{\forall i,\Re^{-1}(i)\neq\emptyset} \\ \qquad\qquad\qquad (\lambda_i)_{\forall i,\Re^{-1}(i)=\emptyset} \end{cases} \tag{2}$$

Assuming all nodes have equal amount of energy in the beginning, we have

$$E_1 = E_2 = \ldots = E_n \tag{3}$$

The system of equations can be solved, assuming the switching energy to be negligible, to get the values of 't_i's. Since a node can have more than one qualifying neighbor that can act as a relay, the sink has to evaluate a number of such combinations using some simple heuristics like simulated annealing or genetic algorithms. However, only those nodes whose distance from the sink is less than the source's distance from the sink are considered as a relay candiate. The worst case algorithmic complexity of the optimization algorithm can be easily calculated to be = number of nodes * average number of neighbors for each node * alpha, where 'alpha' indicates the fraction of those neighbors that can act as relay nodes (can be assumed to be half).

B. *Data Aggregation*

The sink forms a connectivity graph of the nodes in the network and arranges them in tiers starting from itself as level zero. All nodes equidistance from sink after the scheduling phase constitute the same level. This is to ensure that only alternate levels transmit during any beacon interval. Such an arrangement would prevent a node from being forced to transmit and listen simultaneously. If a new node comes into the network, it listens for the IDs of the nodes in the network which allows it to chose an ID that is not present. It then transmits its ID as others did initially. The surrounding nodes when they get this ID send a ranging pulse in the next beacon cycle. After it gets the ranging info, it transmits this info to the sink which calculates a new schedule for both the new node and its one hop neighbors assuming bi-directional links.

IV. SYSTEM DESIGN AND SIMULATION SETUP

We present some key ideas behind the design choices and describe the simulation setup being used to evaluate the proposal.

A. *System Design*

The choice of modulation scheme affects a UWB system both through its inherent E_b/N_0 performance and through its effects on the Power Spectral Density (PSD) of the UWB signal. BPSK eliminates the spectral lines in PSD that could, otherwise, reduce performance by limiting the total transmit power. Its uses anitpodal signalling that has the greatest distance for the same bit energy per bit as compared to PPM and OOK which provides a 3dB advantage in efficiency to achieve the same bit error rate. Use of coherent detection because of BPSK modulation alleviates the need to recover the carrier frequency and phase separately from the symbol clock as they are the same in case of BPSK UWB making the implementation simple. Also, a true optimal RAKE combining receiver is available. For FEC, [2] suggests the use of low-rate binary codes, either binary convolutional or long block codes. We plan to use the sub-code of 2nd order Reed Muller code for the physical header as suggested in [4]. The suggested code has three advantages - optimal in the sense of minimum distance, can use soft decoding and is based on IFHT (Inverse Fast Hadamard Transform) technique which reduces the hardware complexity. MAC layer attaches MAC header and MAC payload and FCS (Frame Check Sequence) and the Physical layer calculate the HCS (Header Check Sequence) of PHY and MAC header and attache the HCS and preamble to MAC header. After the attaching process, the physical header is coded by proposed coding scheme and the rest of the frame may be coded by convolution or turbo code.

B. *Simulation Setup*

The simulation setup consists of matlab models for the transmitter side components - a channel coder for FEC, a modulator to convert bits into symbols, a pulse generator transforming symbols into analog signals, an antenna for radiating the analog signals. On the receiver side, the model has an antenna to collect the received energy, a demodulator to transform the analog waveforms into digital symbols, a synchronisation block, a template signal generator, a channel estimator and a channel decoder. We intend to experiment with different types of receivers - matched filter, RAKE and MMSE and hence we have provisions for adding/removing/modifying different blocks (e.g. a signal generator can be used for providing template signals for correlation based receivers or filter coefficients for matched filter based receivers). The outdoor channel is modelled on the lines of the free space model but with a path loss exponent of four. The indoor propagation model has been adopted from IEEE 802.15.3a standard.

V. FUTURE DIRECTIONS

We intend to compare the performance of the proposed Time Offset based multiplexing algorithm with different algorithms existing in the literature for sensor networks in terms of energy comsumption, network lifetime and computational complexity.

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