Dynamic Huffman Addressing in Wireless Sensor Networks Based on the Energy Map

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***Abstract*— This paper introduces a new dynamic addressing technique for prolonging the operational duration of duty cycled wake-up radios found in wireless sensor networks. A wireless sensor network (WSN) consists of a field of spatially distributed wireless nodes which operate on minimal battery power for extremely long times. A WSN typically uses a multi-hop architecture where messages containing sensed data at the point of origin move through the network eventually finding a gateway node. To minimize energy consumption nodes in a WSN employ novel techniques such as powering down as many components as possible as often as possible. One such MAC technique used is to power down the entire radio, waking up to listen for data addressed to the node at a well known time. This listen time is referred to as the *check period*. If the nodes can maintain sufficient time synchronization the time between check periods can be extended, reducing the duty cycle and increasing the operational life of the WSN at the expense of data latency. Traditionally, the size of the addresses used throughout such a WSN is static and uniform. Our proposed system is neither. As is typical in the WSN space we take a systems level perspective and seek to optimize global objectives. Specifically we consider a WSN field of nodes and maximize the useful life of the network. We assume that when any node has insufficient power to be useful, events can no longer be propagated through the WSN and the WSN is no longer operative. Our approach lengthens the life of the WSN by being especially conservative with nodes having low battery power. We investigate prefix-free (Huffman) encoding of the node addresses based on the energy map. That is, nodes with little battery life left will have the advantage of a short address, and therefore check period, so they are able to power down more quickly, while nodes with more battery life left will get longer addresses and require a longer check period. We will review techniques with a similar objective, offer a formal description of our algorithm and demonstrate that this approach prolongs the usefulness of certain sensor networks via Matlab simulation. Our simulation results show that our dynamic addressing technique can lengthen the operational life of a WSN by more than 10% over traditional fixed length addressing.**

***Index Terms*— Sensor Networks, Energy map, Wake-up radio, Huffman coding.**

I. INTRODUCTION

ONE of the defining characteristics of wireless sensor networks is their extremely conservative use of energy. Wireless sensor network (WSN) nodes typically are battery powered and situated in places which make battery changing difficult if not impossible. Events are sensed by the nodes in the WSN and propagated wirelessly short range from node to node until reaching a gateway network device node which is able to carry the information over some more powerful backbone communication technology as pictured in Figure 1.

Here we propose a technique which is able to further improve the longevity of WSNs employing what is known as *duty cycled wake up MAC*. An early example of this approach was the SMAC protocol introduced in [3]. This media access control (MAC) technique activates the nodes only periodically with a short duty cycle. Communication occurs during these active time periods. Such protocols typically require the geographically separated radios to be synchronized in time. *Our approach is able to significantly extend the useful life of duty cycled WSNs with certain operational characteristics.*

A new technique in WSN MAC design has wireless nodes waking up for a “check period” in which the node listens for a preamble containing its address. If the node does not detect its address, the node returns to sleep mode. Our technique can be viewed as a system level improvement on this MAC design. Our dynamic addressing solution assigns shorter addresses to nodes which have lower battery power available allowing them to "wake up" for a shorter time in the standard epoch when no event occurs. Addresses in our system are assigned dynamically as time progresses, random events occur which must be communicated to the gateway node, and battery power is therefore drained from the system.

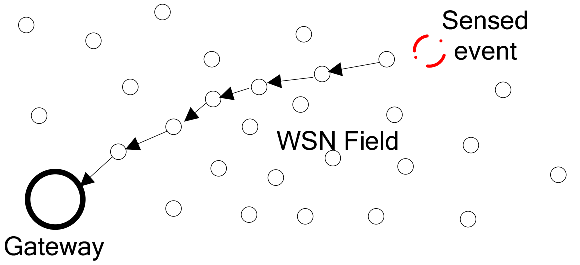

Fig. 1. Wireless Sensor Network Architecture

Our addresses therefore depend on what’s known as the *energy map* of the WSN, the system wide battery power left in the network. Our technique requires global coordination of address updates which is not included in our analysis, but could be accomplished via a short reserved broadcast address used by a powerful gateway node to broadcast management data to the WSN nodes in the network. In the reverse direction, data concerning the energy left in the network nodes could be appended in some approximated fashion to messages carrying sensed events. In the absence of sensed events the remaining battery life of wireless nodes in the WSN can be

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computed explicitly without requiring any communication from the nodes. Since the addresses and duty cycle period of the system is global information, known by the gateway node, the gateway node can compute the energy consumption of an individual node based on the number of time periods which have passed. Given a sensed event the non-determinism associated with events and communication collisions can be reflected precisely in the successful message which finally reaches the gateway node. Since the system we describe consists of uniquely addressed nodes, only those nodes involved in the transfer of a message consume more energy during an epoch than they would during an eventful epoch. And this power consumption can be reported explicitly in the successfully transferred data.

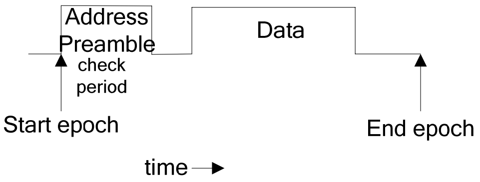

Fig. 2. Wake-up Radio Check-period

Eventually, as with all active radio networks relying on battery power, nodes have insufficient power to transmit enough radio energy to communicate with their neighboring nodes and the network is no longer able to reliably report sensed events. In our WSN simulation we have defined a threshold for this energy level and declare the network incapacitated when the energy level of any node falls below this threshold. Our chain is only as strong as its weakest link.

Networked communication systems utilizing non-uniform address length are rare. Protocol designers typically define a fixed length field for addresses and possibly introduce some technique to ensure uniqueness. Exceptions include original versions of IP and the Self Delimiting Numerical Value (SDNV) addresses in DTN [9]. Real time dynamic addressing is another protocol characteristic which is rare. A ubiquitous example of semi-static dynamic addressing is Dynamic Host Configuration Protocol (DHCP), RFC 2131, in an IP host system being initialized. Performance gains are usually not worth the complexity of utilizing variable length dynamic addressing. The algorithm we propose, however, is designed for wireless systems carrying infrequent, short, non-time critical data which can actually exhibit significant performance gains by exploiting this parameter.

Our variable length addressing requirements are similar to that faced in the source coding problem of text compression where entities (text characters or radio nodes) must be represented by binary strings dependent on some weight (frequency of occurrence or battery life). Huffman coding, perhaps more correctly known as prefix-free encoding, has proven to be a useful technique for symbol compression. Originally it was used for text compression. Today, it is found in JPEG image formats and UNIX compression algorithms. Huffman coding provides an accessible algorithm to encode the addresses of nodes in our sensor network field. Essentially, we seek to make the address length directly proportional to the amount of battery power left in the sensor node.

The sort of sensor networks we have in mind consist of numerous low power nodes which are left for a very long time, possibly years, utilizing an extremely low duty cycle. In a cycle when nothing happens, that is no sensor information is generated and no neighboring nodes have information to be relayed by the node, the node simply wakes up to listen for its address and then goes back to sleep. In general we seek to make this “wake up time”, or standard duty cycle, as short as possible allowing the node to spend the vast majority of its time asleep minimizing its power consumption. Taking the system level view of the sensor network field we observe that as the nodes in the network are depleted of power they are unable to relay data from other nodes and the sensor network becomes useless

To experiment with the effectiveness of our technique and validate our approach we have created a matlab based WSN simulation where events occur randomly and data is passed through the network to the gateway node. Our simulation is oriented with a gateway node at the bottom left which is the destination of all event messaging traffic. We are inspired by the simulator based on the tinyos operating system, tossim [12]. We have based our initial energy, energy consumption, and event occurrence on surveys found in the literature and hardware in the lab. Details of our experiment are given in Section IV.

II. BACKGROUND

In the quest to build lightweight, coordinated, long-lived, massively-distributed wireless networks, the core qualities in sensor networks, researchers have utilized duty cycled wake-up radios. To further improve performance engineers seek to reduce the duty cycle. One of the original duty cycled wake-up radio MACs was Sensor-MAC, SMAC [3]. The S-MAC protocol utilizes periodic listen and sleep, but does not attempt to synchronize the nodes, instead relying on random access and statistical intersection. In experiments the protocol was still effective when the duty cycle was reduced to almost 10% (200ms off, 2s on).

WSN MAC research has since flourished, resulting in an alphabet soup of protocols, at least 32 MAC implementations at last count [8]. Original implementations did not require time synchronization between the nodes and relied on standard CSMA techniques, but simply at a slower time scale. By randomizing the wake-up times, standard, robust wireless protocols can be utilized under this slight modification. Researchers have also investigated separating the data plane and wake-up plane by employing distinct radios for each function. In such a system our technique can be employed in the wake-up plane to improve the operational duration of the system.

Another technique which has found some favor in WSN MAC design is the use of staggered, but deterministic, epochs where a WSN node maintains the schedule of neighboring nodes. In such architectures a WSN node can transmit to its destination when the neighboring WSN is listening. If the nodes are addressable our technique can be employed in such a system to improve the performance of the WSN.

MAC designs which benefit from dynamic Huffman addressing require synchronization of wake-up times so communication between nodes can occur in a more deterministic fashion. This raises the issue of time synchronization between nodes with inexpensive clocks prone to drift. In fact this topic has spurred a flurry of research work in wireless synchronization, physics approaches to ensuring stable oscillations, and advanced phase locked loop (PLL) technologies.

A. Huffman Coding

Huffman coding was originally developed in 1952 as a method for lossless data compression [4]. Symbols are taken along with a weight, typically the symbol's frequency in the string to be compressed, and each symbol is encoded as variable length binary string. For example in a text compression problem a frequently occuring 'a' may become 01 while a rare 'q' may be assigned a 10110. Huffman coding can be shown to be optimal for symbol-by-symbol coding with known input probability distribution [5].

In our approach the symbols are radio nodes and the weights are the inverse of the battery power left in the nodes. Therefore low power nodes will be weighted more heavily than those with more power and will then be assigned shorter addresses. The Huffman algorithm is well known and ubiquitous, see for example [10].

B. Trajectory Based Forwarding

One example of dynamic network behavior based on the energy map is the use of dynamic trajectory based forwarding (TBF) derived from the energy map [1]. Originally simply used to define robust routing paths through sensor fields consisting of non-deterministically scattered radio nodes [7], TBF was then modified to perform under system feedback from the energy map of the WSN. Briefly, this technique utilizes parameterized curves so that packets may avoid dead spots, or areas of the network with low battery power, as they occur during the life of the sensor network. Simulations somewhat similar to those presented in this research demonstrated that the TBF based on Energy Data Dissemination (TEDD) utilized up to 30% less energy than simple TBF.

III. OUR APPROACH

In this section we offer a more formal description of our WSN protocol. We show how the addresses in our system are computed and how they are used in an address aware duty cycled wake-up radio. The primary tool we use is called the *Huffman template algorithm* which is an extension of the original Huffman algorithm for arbitrary weights. The weights in our case are the inverse of the battery power. Just as the more frequent characters in a Huffman compressed text string are assigned the shorter binary strings, our system assigns the nodes with less battery power the shorter strings. Certain issues are not addressed in this initial presentation such as computation of the energy map, collision avoidance, and routing. While such issues are not completely orthogonal to our technique we believe the state of the art techniques can easily be incorporated into our system and will not have a significant effect. In subsequent work we intend to report on complete system implementations which address all of the other difficulties present in fielded WSN systems.

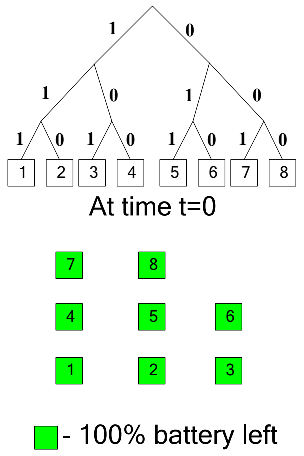

Fig. 3. Addressing of Nodes at Initial Deployment

Consider a set of n WSN nodes $\{D_1,\dots,D_n\}$. At any particular time t each node has a certain positive battery energy left in it $\{B_1(t),\dots,B_n(t)\}$ which can be measured in joules. As time progresses in our system of WSN nodes events occur which consume battery power and energy is reduced so that for any particular node $D_n, B_i(t_1) \ge B_i(t_2)\, for\ t_2 \ge t_1$.

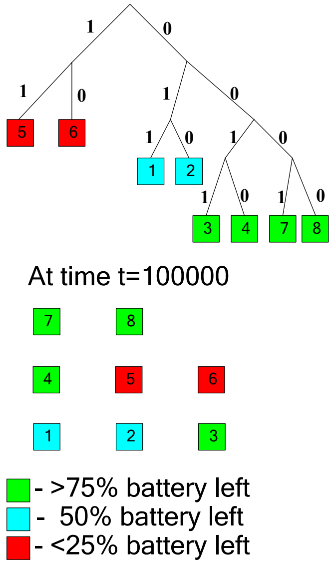

Fig. 4. Addressing of Nodes Near End of Deployment

For our system we look at periods, likely some multiple of the epoch, and define *coordination instances* at periodic intervals $\{T_1, T_2, \ldots\}$. At each coordination instance T_i the Huffman template algorithm is executed on the WSN nodes $\{D_1, \ldots, D_n\}$ utilizing the inverse of their remaining battery energy as the Huffman weights $\left\{ {}^{1}\!/\!{}_{B_1(T_i)}, \ldots, {}^{1}\!/\!{}_{B_n(T_i)} \right\}$. The algorithm iteratively builds a binary tree from the bottom up by selecting the node with the lowest weight ${}^{1}\!/\!{}_{B_j(t)}$. When all nodes have been selected a binary tree is formed with the highest weight nodes (lowest battery energy) at the upper leaves of the tree and the lowest weight nodes (highest battery energy) at the lowest leaves of the tree. The edges of the tree are labeled 0 and 1 and prefix free binary codewords are formed by following the tree from the root to the leaf node. The codeword for a node is then assigned to that node as its address in the WSN. This address remains the node's WSN address until the next coordination instance T_{i+1} when the Huffman template algorithm is again executed based on the current battery energies found in the system $\{B_1(T_{i+1}), \ldots, B_n(T_{i+1})\}$. This process continues for the entire life of the WSN.

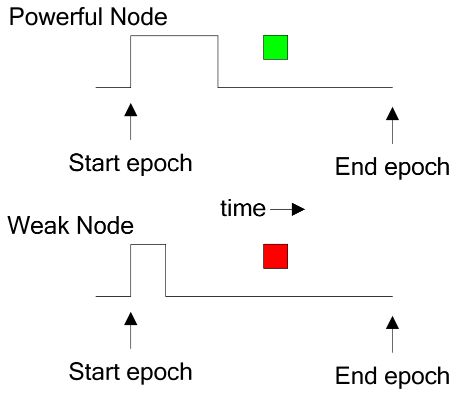

Fig. 5. Duty Cycle During Uneventful Epoch

When the algorithm begins (at time t=0) all nodes have an address length of $\log_2(n)$ where n is the total number of nodes. This is equivalent to the standard flat addressing used in current systems. In the example depicted in Figure 3 sensor network scenario at time t=0 has address(1) = 111 and address(8)=000.

As time progresses the sensor network's centralized management scheme modifies the sensor nodes` addresses based on the energy map and the Huffman template algorithm described in this section, giving the low energy node short addresses and the high energy nodes long addresses. Figure 4 depicts one possible outcome at time t=100000. Nodes 5 and 6 have lost most of their battery power and therefore have short addresses, 11 and 10, respectively. Nodes 1 and 2 have more battery power left and therefore have slightly longer addresses, 011 and 010 respectively. Nodes 3, 4, 7, and 8 have not lost much of their battery power and therefore have the longest addresses 0011, 0010, 0001, and 0000, respectively. Notice that Nodes 3, 4, 7, and 8 have longer addresses than they began with in Figure 3. This is the nature of Huffman compression algorithms and the implementation must allow for address length growth.

In the current work we have not addressed the distributed coordination required to implement our scheme. We have assumed that the nodes have global information and the energy map and addresses obtained via the Huffman template algorithm are available to all of the nodes in the WSN. The management coordination scheme and computation of the energy map is out of the scope of this preliminary report, but one common scenario would include a powerful management and gateway node. Such a management node could utilize a very short reserved broadcast address. Computation of the energy map is an active research topic, see for example [2].

Standard duty cycled WSNs consist of nodes which have one radio and operate on one frequency. Such WSN nodes first listen for their address, the check period, and then for data if a node detects that the address matches and the data is intended for them. A timing diagram reflecting the powered up transitions is shown in Figure 2. A timing diagram illustrating the distinct behavior of the nodes in our system is shown in Figure 5 in the case when the node's address doesn't match the address (if any) received.

The type of Sensor Network we address in this article is sometimes referred to as a wake up radio where messages consist of a header and payload. The header portion of the message contains solely the destination address. A WSN node can then wake up at a particular well know instant in time, listen for its address, and then go back to sleep if its address is not heard.

Our architecture is particularly useful in wireless networks which carry little information. In such networks the vast majority of the time the nodes simply wake up, don't hear their address, then go back to sleep. Our dynamic addressing coordination effort is only warranted in scenarios where virtually all of the nodes` energy is spent listening for its

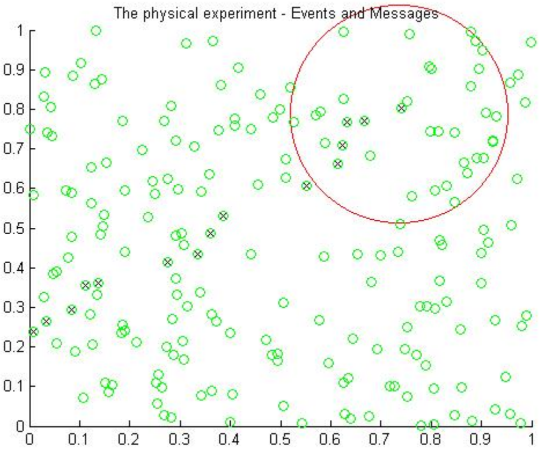

Fig. 6. Our Simulation Visualization

address. In such deployments the energy spent actually transferring data is less. A more active network, typically under high utilization, would likely benefit less from the technique introduced here.

As events occur and data is transferred through the network from the event location to the gateway node battery power is depleted unevenly throughout the network so that some nodes will have consumed most of their battery life while others will have consumed less. Our objective function is driven by the adage "a chain is only as strong as the weakest link". We seek to maintain battery life throughout the network specifically by keeping the node with the lowest battery level operational so that it can still transfer data and the WSN can still perform its function. We define the WSN as being dead when any node in the network no longer has sufficient power to transmit data.

IV. SIMULATION RESULTS

To validate and characterize our algorithm we have created a WSN simulation using the computer software package, Matlab. We have implemented our algorithm in Matlab and tested it in a simulated wireless sensor network.

Our simulation doesn't take into account battery leakage, CPU power consumption, sensing energy or transition energy. We believe that in the sort of networks we address these contributions to energy depletion are insignificant compared to the energy used performing RF functions such as transmitting and listening for wireless data.

The typical military WSN serving the most demanding environment includes a gateway node placed in the middle of some randomly distributed significantly less expensive nodes. Such a scenario includes CONOPS where cheap sensors are, for example, thrown from an Unmanned Aerial Vehicle (UAV). We have only simulated one quadrant of a WSN by placing the gateway node at the lower left and a set of nodes distributed uniformly on a unit square. For the experiments depicted in this section we have used 200 sensor nodes.

Our simulation makes certain assumptions which we have tried to base on sensor networks deployed in the real world and techniques which have been shown to be effective via modern research. AA batteries are a common choice for powering sensor network nodes due to their wide availability, low expense, and high power. AA batteries are often rated at 3000 mAhr (milli-Amp hour). At 1.2 volts we choose to assume that a node utilizing a single AA battery contains 12960 joules since 12960 = 3 AHr * 3600 sec/Hr * 1.2 v.

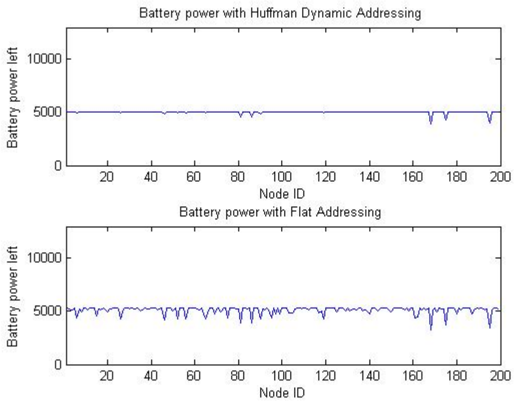

Fig. 7. Battery Power left in Nodes Near End of Operational Life

In the piconet project [6] researchers characterized power requirements in two distinct radio systems. They found the high speed radio consumed 0.5 microjoules per transmission bit, while a lower speed radio with greater range consumed 6 microjoules per bit. In our experiments we have used 5 microjoules per transmission bit to characterize the performance of our energy saving method. We calculate energy depletion during message transfer by multiplying the number of bits transmitted by the chosen number of joules per bit for transmission. During an uneventful epoch the energy consumed is computed by multiplying the number of bits in the nodes address by the number of joules required to receive a bit.

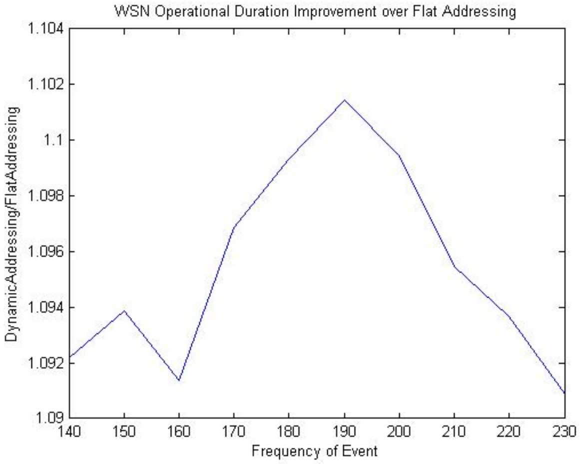

Fig. 8. Improvement in Duration Using Our Technique

For our simulation we chose a simple, deterministic routing protocol. Our protocol could best be described as nearest neighbor closer to the sink. A wireless node containing a message to be forwarded chooses the node which is closest of those nodes left and down from itself. It is somewhat idealized, but might be implemented in a large class of WSNs. Some research has shown that this is often an optimal routing protocol in regards to energy consumption, although pathological examples can be found for which this is not the case. In our experiments events are also chosen uniformly throughout the unit square and occur at a frequency particular to an individual experiment. Figure 8 reflects the results of 10 experiments performed where events are configured to occur deterministically at the period specified on the X-axis. We ran experiments where spatially non-deterministic events occur every 140 to 200 time units. When an event occurs the node closest to the event senses the event and generates a message. The message is routed hop by hop utilizing the duty cycle of the system until it finally arrives at the gateway. The graphic visualization associated with our simulation places a large circle centered at the point the event occurs when the message is generated and as the message is routed through the network as can be seen in Figure 6. Notice that WSN nodes participating in the transfer of the message are marked with an X.

Initial experiments have demonstrated over a 10% improvement in WSN length performance depending on the format of the data. Figure 8 shows that the effectiveness of dynamic Huffman addressing is dependent on the frequency of events occurring in the WSN. For a random scenario where events occur every 140 time units we observed that DHA offered a 9.2% improvement over a similar WSN using standard flat addressing In our experiments our technique demonstrated the most effectiveness for a event periodicity of one event every 190 time units. In the 190 cycle event experiment DHA offered a 10.2% improvement.

We expect that the peak in performance at period 190 observed in Figure 8 is a product of many system parameters which have been chosen somewhat arbitrarily. Different choices of receive power, transmit power, routing algorithm, and message size would most likely lead to a different "sweet spot". The fidelity of our model is such that we are left with only four parameters, receive power, transmit power, routing algorithm, and sensor message size. In subsequent work we expect to do experiments with actual hardware. Still we expect our system to be most effective in environments where events are relatively rare and sensor node lives are extremely long as reflected in our choice of parameters. In such a system we believe our results are accurate and an approximately 10% improvement in operational duration can be achieved.

V. CONCLUSIONS

In this paper, we have presented a novel approach which utilizes dynamic addressing to significantly extend the life of certain types of wireless sensor networks. The technique preserves battery life by assigning shorter address to less powerful nodes as the network is operational. The technique is useful in many types of duty cycled wake-up MAC's and doesn't conflict with other techniques particular to the wireless sensor network domain. It is even complementary to other approaches which have similar objectives such as energy based routing on curves [1].

While much work remains to validate the technique described in this paper, the early results given here appear promising. Next steps include a prototype system consisting of software which implements our dynamic addressing. While general purpose radio systems cannot implement our algorithm due to the rigidity of their RF interface, we believe there are some (low volume) existing systems which include configurable hardware such as FPGAs and can implement our algorithm. One of these systems is the SensorBone radio [11] developed by Argon ST, previously San Diego Research Center.

We believe our dynamic addressing approach is unobtrusive, beneficial, and can be added to virtually any duty cycled WSN system to produce a marked improvement in WSN life. Furthermore the general approach of using dynamic addressing to combat power consumption as introduced here can likely be applied across many other domains.

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