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Hybrid Approach for Energy-Aware Synchronization

Robert Akl, Yanos Saravanos and Mohamad Haidar
University of North Texas
Denton, Texas, USA

1. Introduction

Several sensor applications have been developed over the last few years to monitor environmental properties such as temperature and humidity. One of the most important requirements for these monitoring applications is being unobtrusive, which creates a need for wireless ad-hoc networks using very small sensing nodes. These special networks are called wireless sensor networks (WSN). WSNs are built from many wireless sensors in a high-density configuration to provide redundancy and to monitor a large physical area.
WSNs can be used to detect traffic patterns within a city by tracking the number of vehicles using a designated street (Winjie et al., 2005), (Tubaishat et al., 2008). If an emergency arises, the network can relay the information to the city hall and notify police, fire, and ambulance drivers of congested streets. An application could even be designed that suggests the fastest route to the emergency area. When compared to computer terminals in Local Area Networks (LANs), wireless sensors must operate on very low capacity batteries to minimize their size to about that of a quarter. The nodes use slow processing units to conserve battery power. A typical sensor node such as Crossbow's Mica2DOT operates at 4 MHz with 4 KB of memory and has a radio transceiver operating at up to 15 Kbps (MICA2DOT, 2005). Radio transmissions consume by far the majority of the battery's energy, so even with this low-power hardware, a sensor can easily be depleted within a few hours if it is continuously transmitting.
One of the most common uses for wireless sensor networks is for localization and tracking(Patwari et al., 2005), (Langendoen & Reijers , 2003). Tracking of a single object is relatively simple since data can be handed-off from sensor to sensor as the object moves through the network.
Another important aspect is time synchronization in a networked system. The majority of research in this field has concentrated on traditional high-speed computer networks with few power restraints, leading to the Global Positioning System (GPS) and the Network Time Protocol (NTP), (NTP, 2009). Although GPS is an accurate and commonly used synchronization protocol, there are a few requirements that GPS fails to meet. Some of which are that the receiver is 4.5 inches in diameter, more than 4 times the size of a typical sensor node, and also requires an external power source. These two traits counteract the goal of using small and mobile nodes to create a WSN, not to forget the line-of-sight

requirement that cripples GPS's use for sensor networks dispersed within a building or in a heavily forested area. On the other hand, NTP is one of the first synchronization protocols used for computer systems, first developed in 1985 (NTP, 2009). This protocol uses a relatively large amount of memory to store data for synchronization sources, authentication codes, monitoring options, and access options. As mentioned earlier, typical wireless sensor nodes have limited onboard memory. A large sensor network will require large files for synchronization sources and codes. If these configuration files can be programmed into each node, it would leave very little memory to hold the data monitored by the sensor, limiting NTP's use for WSNs. Furthermore, NTP's synchronization accuracy is within 10 ms over the Internet, and up to 200 µs in a LAN (NTP, 2009); these specifications are inadequate for most sensor network applications. Therefore, new synchronization methods have been developed specifically for sensor networks, such as the reference broadcast synchronization method (RBS) (Elson et al., 2002) and the timing-sync protocol for sensor networks (TPSN) (Ganeriwal, November 2003), (Ganeriwal, 2003).

RBS and TPSN achieve accurate clock synchronization within a few microseconds of uncertainty nonetheless both are designed for networks with a small number of sensors and are not specifically geared towards energy conservation. Although these algorithms tend to work for larger networks, their energy consumption becomes inefficient and network connectivity is broken once nodes begin lacking power. Simulations show that synchronizing a large sensor network requires a large number of transmissions, which will quickly deplete sensors and reduce the network's coverage area.

A time synchronization scheme for wireless sensor networks that aims to save sensor battery power while maintaining network connectivity for as long as possible is presented based on a hybrid algortihm that combines both TPSN and RBS.

This algorithm is an extension of our previous work presented in (Akl & Saravanos, 2007). It focuses on the following aspects of WSNs:

1. Design a hybrid method between RBS and TPSN to reduce the number of transmissions required to synchronize an entire network.
2. Extend single-hop synchronization methods to operate in large multi-hop networks.
3. Verify that the hybrid method operates as desired by simulating against RBS and TPSN.
4. Maintain network connectivity and coverage.

2. Time Synchronization Algorithms in WSNs

Traditional synchronization methods, that are effective for computer networks, are ineffective in sensor networks. New synchronization algorithms specifically designed for wireless sensor networks have been developed and can be used for several applications (Sivirkaya & Yener, 2004). The authors in (Palchaudhuri et al., 2004) present a probabilistic method for clock synchronization based on RBS. In (Sun et al., 2006), the authors present a level-based and a diffusion-based clock synchronization that is resilient to some source nodes. The authors in (He & Kuo, 2006) propose creating spanning trees with multiple subtrees in which two subtree synchronization algorithms can be performed. Four methods are described in (Qun & Rus, 2006) to achieve global synchronization: a node-based, a hierarchal cluster-based, a diffusion-based, and a fault-tolerant based approach. An Efficient

RBS (E-RBS) algorithm is proposed in (Lee et al., 2006) to decrease the number of messages to be processed and save energy consumption within a given accuracy range.

2.1 The Reference Broadcast Synchronization Method (RBS)

Since GPS and NTP are not very effective in wireless sensor applications, the first major research attempts to create a time synchronization algorithm specifically tailored for sensor networks led to the development of reference broadcast synchronization (RBS) in 2002 (Elson et al., 2002). The algorithm defines a critical path, which is represented by the portion of the network where a significant amount of clock uncertainty exists. A long critical path results in high uncertainty and low accuracy in the synchronization. There are four main sources of delays that must be accounted for to have accurate time synchronization:

- *Send time:* this is the time to create the message packet.
- *Access time:* this is a delay when the transmission medium is busy, forcing the message to wait.
- *Propagation time:* this is the delay required for the message to traverse the transmission medium from sender to receiver.
- *Receive time:* similar to the send time, this is the amount of time required for the message to be processed once it is received.

The RBS algorithm can be split into three major events:

1. *Flooding:* a transmitter broadcasts a synchronization request packet.
2. *Recording:* the receivers record their local clock time when they initially pick up the *sync* signal from the transmitter.
3. *Exchange:* the receivers exchange their observations with each other.

RBS synchronizes each set of receivers with each other as opposed to traditional algorithms that synchronize receivers with senders. These latter algorithms have a long critical path, starting from the initial send time until the receive time. For this reason, NTP's accuracy is severely limited, as discussed previously. RBS uses a relative time reference between nodes, eliminating the send and access time uncertainties. The propagation delay of signals is extremely fast from point-to-point, so this delay can be ignored when dealing in the microsecond scale. Lastly, the receive time is reduced since RBS uses a relative difference in times between receivers. Nonetheless, the time of reception is taken when the packet is first received in the MAC layer, eliminating uncertainties introduced by the sensor's processing unit.

There are two unique implementations of RBS. The simplest method is designed for very high accuracy for sparse networks, where transmitters have at most two receivers. The transmitter can broadcast a synchronization request to the two receivers, which will record the times at which they receive the request, just as the algorithm describes. However, the receivers will exchange their observations with each other multiple times, using a linear regression to lower the clock offset. The other version of the RBS algorithm involves the following steps: the transmitter sends a reference packet to two receivers; each receiver checks the time when it receives the reference packet; the receivers exchange their recorded times. The main problems with this scheme are the nondeterministic behavior of the receiver, as well as clock skew. The receiver's nondeterministic behavior can be resolved by simply sending more reference packets. The clock skew is resolved by using the slope of a least-squares linear regression line to match the timing of the crystal oscillators.

RBS can be adapted to work in multi-hop environments as well. Assuming a network has grouped clusters with some overlapping receivers, linear regression can be used to synchronize between receivers that are not immediate neighbors. However, it is more complicated than the single-hop scenario since there will be timestamp conversions as the packet is relayed through nodes. This extra complication is manifested in larger synchronization errors. Fig. 1 shows how a sensor network is synchronized by using RBS.

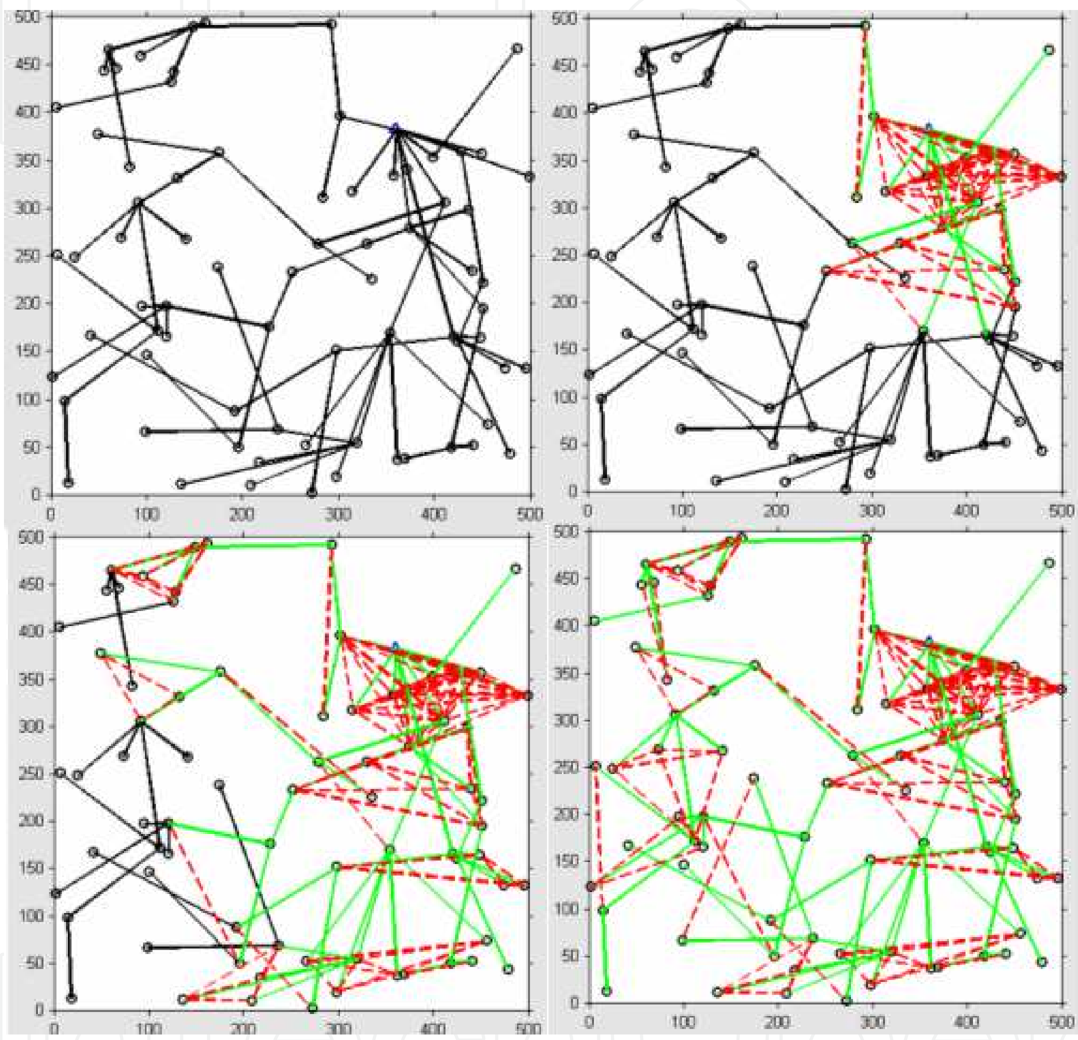

Fig. 1. RBS Synchronization of a Wireless Sensor Network (The initial solid dark lines represent the network's topology after flooding; the solid light lines represent transmitter-to-receivers communication; the dashed lines represent receiver-to-receiver transmissions).

There are some issues with the RBS synchronization algorithm that must be addressed in an energy-aware sensor network. First, the receiver-to-receiver synchronization method is effective at reducing the critical path to increase the accuracy, but RBS scales poorly with dense networks where there are many receivers for each transmitter. Given n receivers for a single transmitter, the number of transmissions increases linearly with n, but the number of receptions increases as $O(n^2)$. The following numbers of transmissions and receptions exist in RBS:

$$TX_{RBS} = n \, , \tag{1}$$

$$RX_{RBS} = n + \sum_{i=1}^{n-1} i = n + \frac{n(n-1)}{2} = \frac{n^2 + n}{2} \quad (2)$$

For a large number of receivers per transmitter, this method becomes infeasible due to energy constraints.

Lastly, RBS does not account for lost network coverage when nodes begin losing power. Should a transmitting node be depleted, all of its receivers will be dropped from the network, so measures should be taken to re-establish connectivity when the coverage decreases beyond some threshold value.

2.2 TheTiming-Sync Protocol

The timing-sync protocol for sensor networks (TPSN) was developed in 2003 in an attempt to further refine time synchronization beyond RBS's capabilities (Ganeriwal, November 2003), (Ganeriwal, 2003). TPSN uses the same sources of uncertainty as RBS does (send, access, propagation, and receive), with the addition of two more:

- *Transmission time:* the time for the packet to be processed and sent through the RF transceiver during transmission.
- *Access time:* the time for each bit to be processed from the RF transceiver during signal reception.

The TPSN works in two phases:

1. *Level Discovery Phase:* this is a very similar approach to the flooding phase in RBS, where a hierarchical tree is created beginning from a root node.
2. *Synchronization Phase:* in this phase, pair-wise synchronization is performed between each transmitter and receiver.

In the level discovery phase, each sensor node is assigned a level according to the hierarchical tree. A pre-determined root node is assigned as level 0 and broadcasts a *level_discovery* packet. Sensors that receive this packet are assigned as children to the transmitter and are set as level 1 (they will ignore subsequent *level_discovery* packets). Each of these nodes broadcasts a *level_discovery* packet, and the pattern continues with the level 2 nodes.

In the synchronization phase, pair-wise synchronization is performed between the transmitter and receiver nodes using a 2-way handshake.

Although RBS removes the uncertainty at the sender by exchanging times amongst receivers, TPSN reduces the remaining uncertainties by a factor of 2 due to the handshake process that averages the clock drift and propagation delay. However, TPSN's uncertainty at the sender can be reduced to an insignificant delay by time-stamping at the MAC layer just before the bits are sent through the transceiver.

The number of transmitters and receivers in TPSN are as follows:

$$TX_{TPSN} = n + 1, \quad (3)$$

$$RX_{TPSN} = 2n. \quad (4)$$

Fig. 2 shows how a sensor network is synchronized by using TPSN.

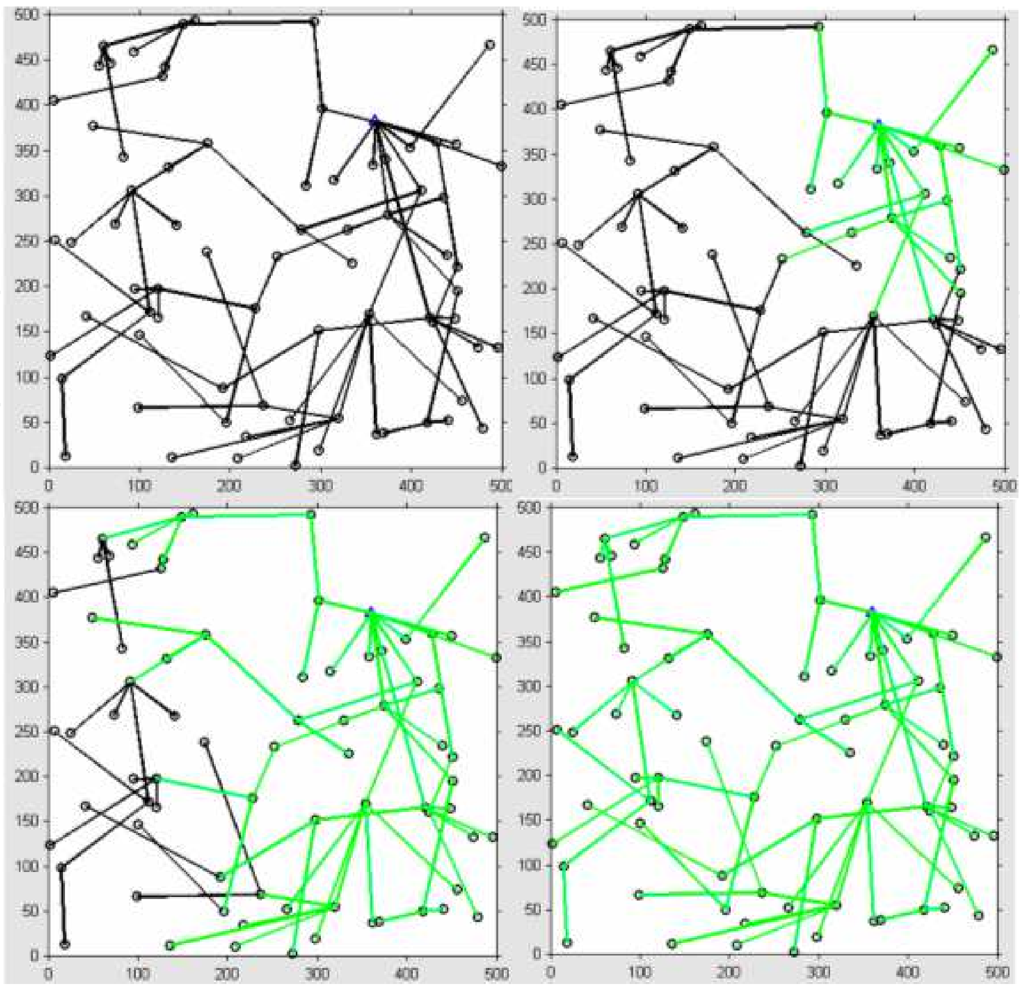

Fig. 2. TPSN Synchronization of a Wireless Sensor Network (The initial solid dark lines represent the network's topology after flooding; the subsequent light lines represent successful transmitter-to-receiver synchronizations).

TPSN is a great improvement over RBS in terms of accuracy since it employs a 2-way handshake, which reduces uncertainty to half since the average of the time differences is used. However, the main drawback TPSN faces is that it consumes energy in sparse networks; a 2-way handshake requires each node to receive a packet and to send one in response. In addition, TPSN shares the same problem with RBS with respect to lost network coverage when nodes begin losing power. A dead transmitter node will drop all of its receivers from the network, lowering the WSN's coverage area. Network restructuring is not included in the TPSN algorithm.

RBS and TPSN are some of the first efforts in creating synchronization algorithms tailored towards low-power sensor networks. They both have unique strengths when dealing with energy consumption. RBS is most effective in networks where transmitting sensors have few receivers, while TPSN excels when transmitters have many receivers.

2.3 Energy-Aware Time Sychronization

A new hybrid algorithm is proposed in this section.

2.3.1 Hybrid Flooding

Before the sensors can be synchronized, a network topology must be created. Table 1 shows the algorithm for the hybrid flooding algorithm that is used by each sensor node to efficiently flood the network.

Algorithm 1: Hybrid Flooding Algorithm

Accept *flood_packets*
Set *receiver_threshold* to *low_power*
Set *num_receivers* to 0
If *current_node* is root node
    Broadcast *flood_packet*
Else If *current_node* receives *flood_packet* and is accepting them
    Set parent of *current_node* to source of broadcast
    Set *current_node* level to parent's node level + 1
    Rebroadcast flood request with *current_node* ID and level
    Broadcast *ack_packet* with *current_node* ID
    Ignore subsequent *flood_packets*
Else If *current_node* receives *ack_packet*
    Increment *num_receivers*

Table 1. The Hybrid Flooding algorithm

Each sensor is initially set to accept *flood_packets*, but will ignore subsequent ones in order not to be continuously reassigned as the flood broadcast propagates. The *num_receivers* variable keeps track of the node's receivers and is used in the synchronization algorithm.

2.3.2 Hybrid Synchronization

Once the network flooding has been completed, the network can be synchronized using the determined hierarchy. In networks where the sensors are dispersed at random, there will be patches of high density node distribution interspersed with lower density regions. A transmitter in a high density area will usually have a large number of receivers, while another transmitter in a lower density section will usually have 1 or 2 receivers at most. As discussed in the previous sections, RBS excels when the transmitter has few receivers and TPSN excels with many receivers connected to each transmitter.

The hybrid algorithm minimizes power regardless of the network's topology by choosing the best synchronization technique depending on the number of children connected to the transmitter. Since the energy required for reception usually differs from that of a transmission, the ratio of the reception power to the transmission power is needed in order to find the optimal point at which to switch from receiver-receiver synchronization to transmitter-receiver synchronization. In order to find the ratio of reception-to-transmission power, α, we combine equations (1), (2), (3), and (4):

$$\alpha = \frac{TX_{TPSN} - TX_{RBS}}{RX_{RBS} - RX_{TPSN}} = \frac{2n}{-(n^2 - 3n)} \tag{5}$$

In general, the following equation can be used to determine the *receiver_threshold* by solving equation (5) for n:

$$n^2 - 3n - \frac{2}{\alpha} = 0 \tag{6}$$

Table 2 shows the algorithm for the hybrid Synchronization algorithm.

Algorithm 2: Hybrid Synchronization Algorithm
Set *receiver_threshold* to *high_power*
If *num_receivers* < *receiver_threshold // Use RBS algorithm*
Transmitter broadcasts *sync_request*
For each receiver
Record local time of reception for *sync_request*
Broadcast *observation_packet*
Receive *observation_packet* from other receivers
Else *// Use TPSN algorithm*
Transmitter broadcasts *sync_request*
For each receiver
Record local time of reception for *sync_request*
Broadcast *ack_packet* to transmitter with local time

Table 2. The Hybrid Synchronization Algorithm

2.3.3 Energy Depletion

Another issue that the hybrid algorithm addresses when synchronizing a sensor network is the effect that a depleted sensor has on the topology. Once the battery is exhausted, the node will be dropped from the network, but so will all of the receivers depending on it. This loss of connectivity cascades through each receiver, so a drastic restructuring can occur when a high-level sensor is drained. The hybrid algorithm keeps track of the number of powered nodes. Once this number decreases below another user-defined threshold, the network is re-flooded using the flooding algorithm described earlier in Table 2. Should the source node lose power, a new source node is chosen from the original one's receivers. These receivers communicate their power levels with each other and the one with the most remaining energy is elected as the new root node, as show in Table 3.

Algorithm 3: Root Node Election Algorithm

If *cur_node_level* == 1 and *cur_node_power* allows 1 more TX
    Broadcast *elect_packet* with *cur_node_ID*
If *cur_node_level* == 2
    Broadcast *elect_packet* with *cur_node_ID*, *cur_node_power*
    If *cur_node* receives *elect_packet* and *elect_packet_power* >= *cur_node_power*
        Set *elect_packet_ID* to root node

Table 3. The Root Node Election Algorithm

In addition, receivers will only analyze the *sync_request* packets from their respective transmitters when using the TPSN-style synchronization. This saves additional battery power since the receivers do not have to analyze packets they overhear from other broadcasting transmitters. Lastly, the dropped packets are monitored. This is a useful statistic since it keeps track of algorithm efficiency and wasted energy. Dropped packets also allow us to compare various network topologies and determine which ones allow for the most energy conservation.

3. Results and Analysis

3.1 Hybrid Algorithm Validation

Several simulations were run to compare the power consumption of the TPSN, the RBS, and our hybrid algorithm discussed in the previous section. A transmitting sensor can dynamically switch between RBS and TPSN by simply comparing the number of connected receivers to the reception/transmission power ratio. This ratio is changed in order to observe how each of the algorithms is affected. All other parameters are kept constant. Our simulations are run on a 1000m x 1000m area, which is randomly populated with 500 sensors, and the path loss coefficient is set to 3.5. In each simulation, the *receiver_threshold* value is changed from 1 to the largest number of receivers connected to a sensor. The hybrid synchronization algorithm is executed for each of these *receiver_threshold* values and the energy consumption is stored and compared to the consumption of TPSN, RBS, and the optimal hybrid synchronization algorithm. Each of the data points is plotted, along with a line representing the average from all of the simulations. For the MICA2Dot platform, a reception uses approximately 24 mW of power, while a transmission requires 75 mW at -5 dBm (MICA2DOT, 2005). Solving for a and n in equations (5) and (6), we get a= 0.32 and n= 4.42, respectively.

The hybrid algorithm will use the least amount of energy when the *receiver_threshold* is set to 4.42. This means that transmitters with 4 or fewer sensors will use RBS for synchronization while those with 5 or more receivers will use TPSN. Fig. 3 illustrates how changes in the *receiver_threshold* value affect the hybrid algorithm.

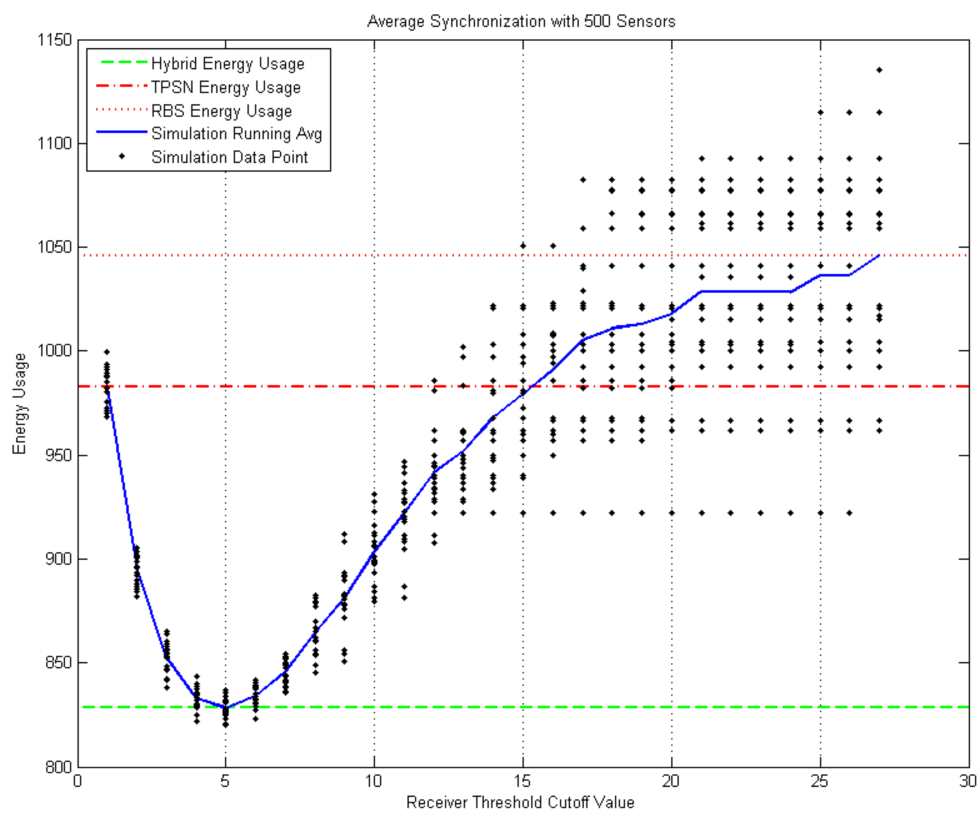

Fig. 3. Mica2DOT Synchronization Comparison

The energy consumption from the hybrid algorithm when using the optimal *receiver_threshold* value is lower than both TPSN and RBS. The minimum value is found between values of 4 and 5. Lastly, the spread amongst data points increases dramatically as the receiver threshold increases beyond 13.

More importantly, setting the *receiver_threshold* value to 1 will force a transmitter to use TPSN. The hybrid algorithm in this case will have the same energy consumption as TPSN. On the other hand, a *receiver_threshold* set to the largest number of receivers connected to a transmitter will force a transmitter to use RBS.

The hybrid synchronization algorithm is very dynamic and will adapt itself to multiple equipment specifications. The power requirements for the MicaZ sensor platform are drastically different from the Mica2DOT platform; MicaZ uses 59.1 mW for a reception, but only uses 42 mW for each transmission at -5 dBm (MICAz, 2005). Similarly, solving for a and n in equations (5) and (6), we get a= 1.407 and n= 3.42, respectively. When using MicaZ, the optimal *receiver_threshold* value is 3.42. This property is reflected in Fig. 4.,where the local minimum has shifted further to the left when compared to the Mica2DOT platform.

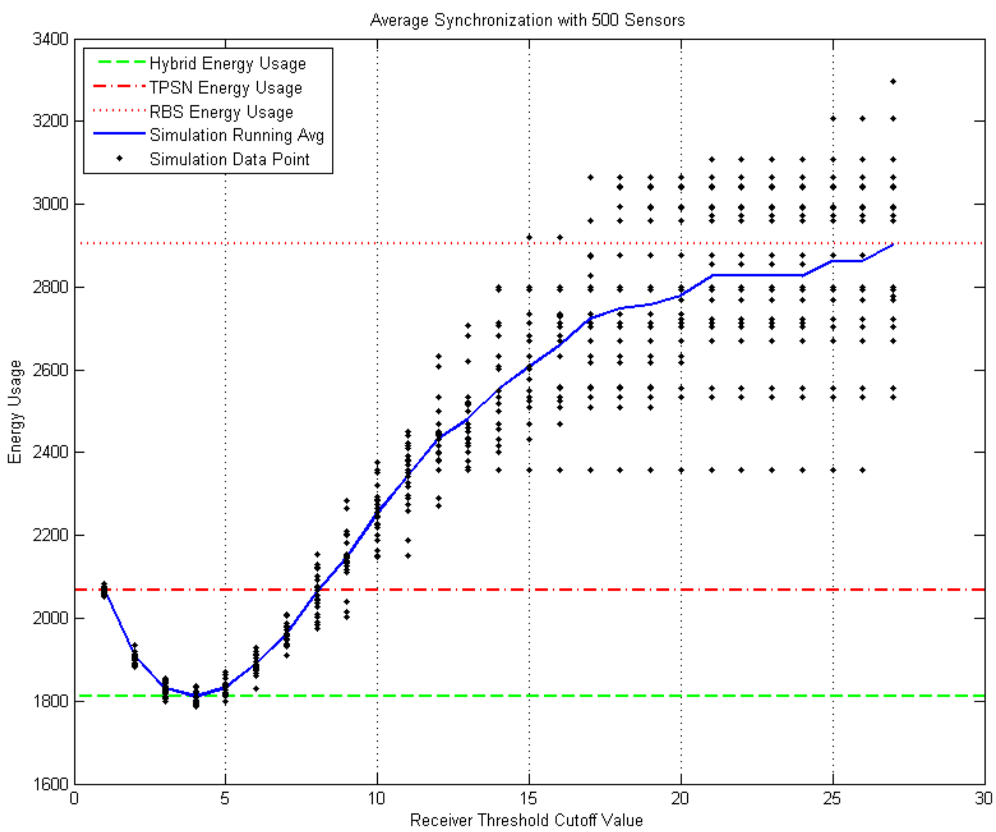

Fig. 4. MicaZ Synchronization Comparison

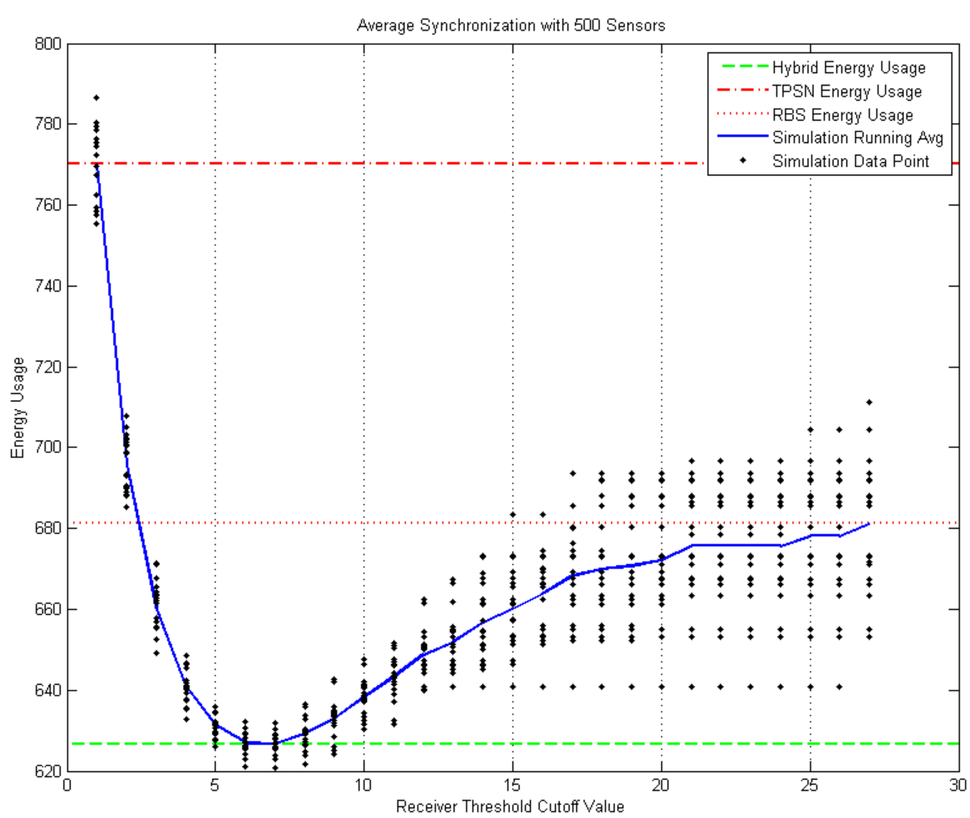

Fig. 5. Synchronization Comparison for Architecture with n=6

Despite the differences in architecture, both of the above examples yield relatively similar values for the optimal *receiver_threshold*. Assume that there is an improvement in the Mica2DOT platform which allows for much lower power in receiving mode. Each transmission still requires 75 mW at -5 dBm, but only 8 mW is needed for a reception. Then, a and n from equations (5) and (6) are 0.107 and 6, respectively. Fig. 5 illustrates the energy usage when the *receiver_threshold* changes.

In this particular example, the hybrid algorithm produces a local minimum when using the optimal *receiver_threshold*, as was expected. It is also interesting to note that now, RBS becomes more energy efficient than TPSN.

3.2 Power Consumption

The next set of simulations demonstrates the algorithm's reduction in power consumption in several network sizes. The number of sensors was changed from 250 up to 1500, in increments of 250. Just as before, 20 simulations were run over a 1000m x 1000m area which was randomly populated with 500 sensors, and the path loss coefficient was set to 3.5. The Mica2DOT platform was used and the ratio of reception/transmission power remained fixed. The *receiver_threshold* value is once again changed from 1 to the largest number of receivers connected to a sensor. The hybrid synchronization algorithm is executed for each of these *receiver_threshold* values and the energy consumption is stored and compared to the consumption of TPSN, RBS, and the optimal hybrid synchronization algorithm. Each of the data points is plotted, along with a line representing the average from all of the simulations as show in Fig. 6, Fig. 7, and Fig. 8.

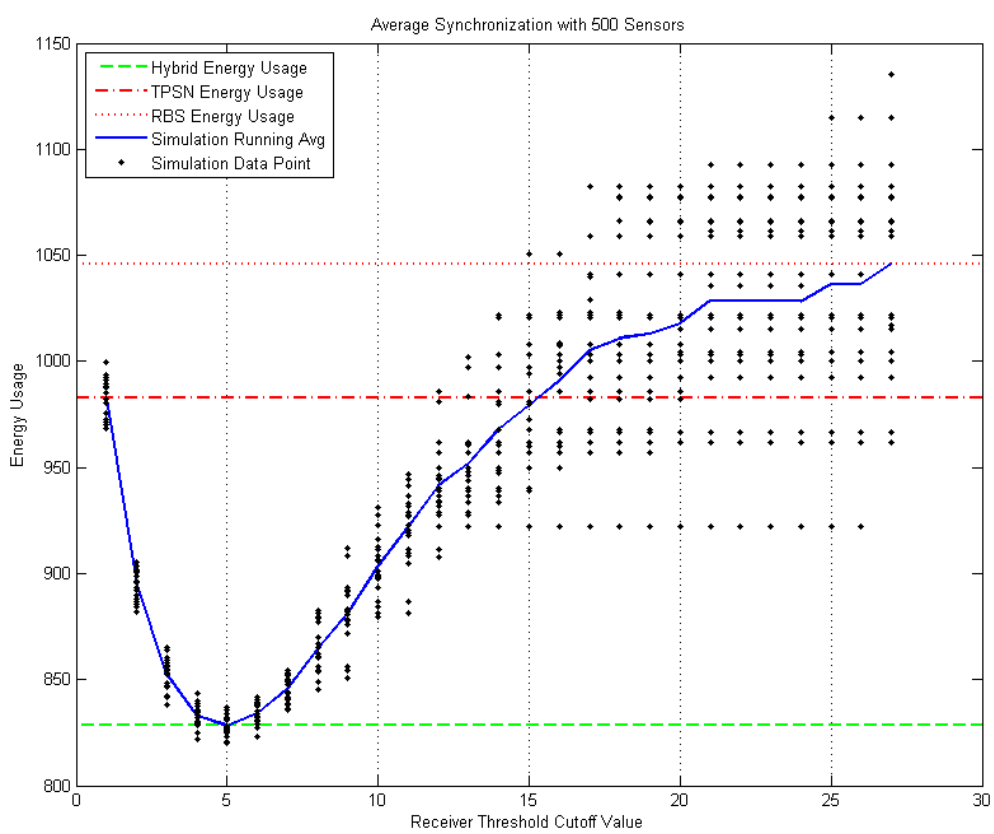

Fig. 6. Energy usage consumption for 500 sensors between RBS, TPSN, and our Hybrid algorithm for different values of *receiver_threshold* values using Mica2Dot platform. Energy usage is in mW.

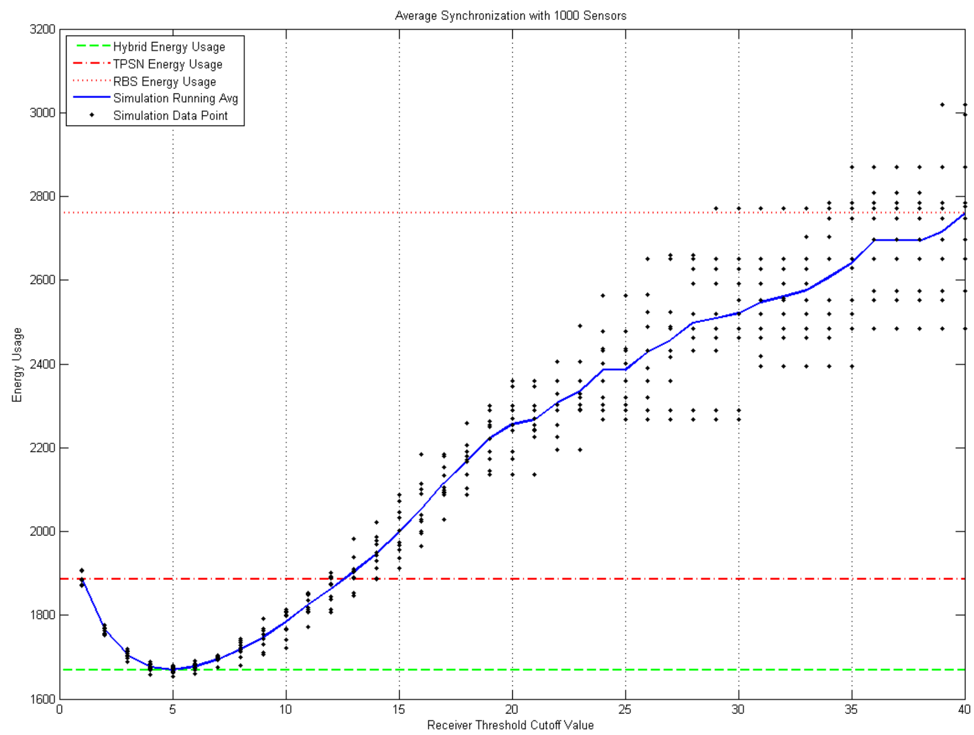

Fig. 7.Energy usage consumption for 1000 sensors between RBS, TPSN, and our Hybrid algorithm for different values of *receiver_threshold* values using Mica2Dot platform. Energy usage is in mW.

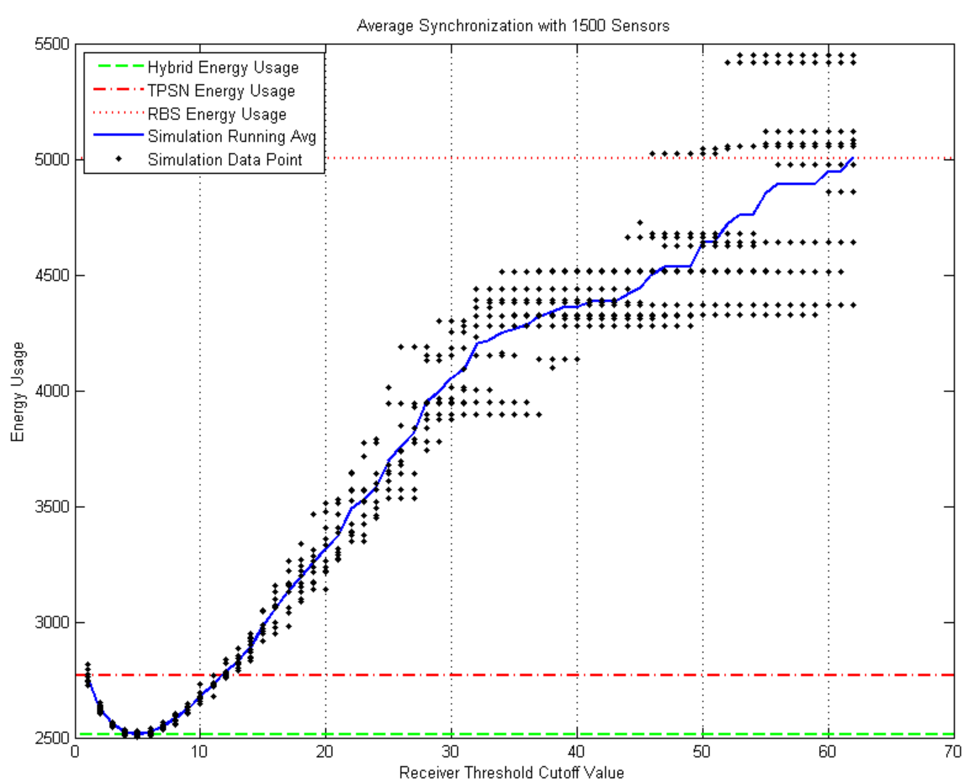

Fig. 8. Energy usage consumption for 1500 sensors between RBS, TPSN, and our Hybrid algorithm for different values of *receiver_threshold* values using Mica2Dot platform. Energy usage is in mW.

As more sensors are introduced into the network, RBS becomes dramatically less feasible for a wireless sensor network. As shown in Table 4, the hybrid algorithm's energy savings over RBS increases from 58% with 750 sensors to over 74% when the network uses 1500 sensors.

Sensors	250	500	750	1000	1250	1500
RBS	615	1709	3421	5510	7833	11128
TPSN	498	998	1498	1998	2498	2998
Hybrid	447	924	1415	1898	2386	2879
RBS Savings	27.44 %	45.94 %	58.65 %	65.55 %	69.54 %	74.13 %
TPSN Savings	10.27 %	7.43 %	5.57 %	4.99 %	4.47 %	3.97 %

Table 4. Average Number of Receptions

In contrast, as the network becomes large, the hybrid algorithm mimics TPSN's behavior, but uses less energy. The difference is 5.57% with 750 sensors and 3.97% with 1500 sensors. Although the number of receptions when using TPSN increases linearly with network size, this number increases much more quickly when using RBS. The hybrid algorithm greatly reduces the number of receptions when compared to RBS; for small networks, the advantage is 27%, but it increases to over 74% in networks with a large number of sensors. Therefore, the hybrid algorithm has a large advantage over TPSN in small networks, but that advantage decreases as more sensors are added.
Table 5 shows the standard deviation in the number of receptions for each of the synchronization algorithms. These results help to determine how sensitive an algorithm is to modifications in the network's topology and sensor density.

Sensors	250	500	750	1000	1250	1500
RBS	54.71 8.89 %	150.09 8.78 %	365.43 10.68 %	524.32 9.52 %	614.26 7.84 %	1129.50 10.15 %
TPSN	0.73 0.15 %	0.00 0.00 %	0.00 0.00 %	0.00 0.00 %	0.00 0.00 %	0.00 0.00 %
Hybrid	11.73 2.63 %	13.16 1.42 %	15.89 1.12 %	14.75 0.78 %	15.99 0.67 %	16.77 0.58 %

Table 5. Standard Deviation for Receptions

The table above shows that there is very large variation in the number of receptions for RBS, meaning that the number of receptions when using RBS is highly dependent on the topology of the network. The table also shows that the deviation in receptions when using TPSN is usually 0, with the exception once again in the 250 sensor network. This exception is due to orphaned nodes which do not participate in the synchronization. The hybrid algorithm has a relatively low deviation, which decreases further with large numbers of sensors. This behavior is attributed to the hybrid algorithm behaving similarly to TPSN when the network is large.

Another simulation results are shown in Table 6 and Table 7. These results show that RBS's energy consumption is more dependent on the density of sensors in a given area. In contrast, TPSN and the hybrid algorithm are less affected by the size of the network.

Sensors	250	500	750	1000	1250	1500
RBS	446	1046	1844	2762	3756	5060
TPSN	511	983	1434	1885	2331	2770
Hybrid	404	828	1253	1672	2095	2514
RBS Savings	9.29%	20.79%	32.04%	39.46%	44.22%	50.31%
TPSN Savings	20.80%	15.73%	12.65%	11.28%	10.11%	9.23%

Table 6. Average Energy Consumption in mW

Sensors	250	500	750	1000	1250	1500
RBS	17.38 3.90%	48.03 4.59%	116.94 6.34%	167.78 6.07%	196.56 5.23%	361.44 7.14%
TPSN	7.67 1.50%	8.88 0.90%	14.31 1.00%	14.48 0.77%	18.22 0.78%	22.09 0.80%
Hybrid	4.00 0.99%	4.72 0.57%	5.23 0.42%	6.85 0.41%	6.33 0.30%	6.84 0.27%

Table 7. Standard Deviation of Energy Consumption

When the network size increases from 250 sensors to 500 sensors (for the same area of 1 km^2), RBS becomes less energy efficient than TPSN. The hybrid algorithm outperforms TPSN by 15.7%, while outperforming RBS by 20.8%. Once the network increases to 750 sensors, RBS clearly becomes less efficient than TPSN. The hybrid algorithm still outperforms TPSN by 12.7%. Since RBS consumes more energy, the hybrid algorithm now outperforms it by 32%. As more sensors are introduced into the network, RBS becomes dramatically less feasible for a wireless sensor network. As shown in Table I, the hybrid algorithm's energy savings over RBS increases from 39% with 1000 sensors to over 50% when the network uses 1500 sensors. In contrast, as the network becomes large, the hybrid algorithm mimics TPSN's behavior, but uses less energy. The energy savings over TPSN are 11% with 1000 sensors and 9% with 1500 sensors. For extremely large networks (10,000+ sensors) TPSN has the same efficiency as our proposed algorithm.

4. Conclusion and Future Work

Wireless sensor networks have tremendous advantages for monitoring object movement and environmental properties but require some degree of synchronization to achieve the best results. The hybrid synchronization algorithm was designed to switch between Timing-sync Protocol for Sensor Networks (TPSN) and the Reference Broadcast Synchronization algorithm (RBS). These two algorithms allow all the sensors in a network to synchronize themselves within a few microseconds of each other, while at the same time using the least amount of energy possible. The savings in energy varies upon the density of the sensors as well as the reception-to-transmission ratio of energy usage; networks, which are saturated with sensors, for example 1500 sensors in a 1 km^2 area, will favor TPSN over RBS. TPSN also becomes more favorable as receptions consume more power. The hybrid algorithm compromises between both of these previous algorithms. The energy savings over RBS can range from 9.3% in small networks of 250 sensors, to over 50% for large networks using 1500 sensors. In contrast, the hybrid algorithm's savings over TPSN range from 20.8% in the same small networks down to 9% in the large networks. Furthermore, analysis of the standard deviation for each of the algorithms shows RBS's energy consumption can vary dramatically, from nearly 4% to over 7%, generally increasing for larger networks. In contrast, the standard deviation for TPSN's energy usage decreases from 1.5% to less than 1%, generally decreasing for larger networks. The hybrid algorithm's deviation is always less than 1% and continuously decreases to 0.3% as more sensors are used.

5. References

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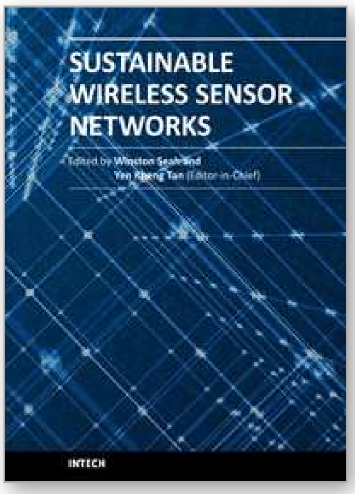

Sustainable Wireless Sensor Networks
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Wireless Sensor Networks came into prominence around the start of this millennium motivated by the omnipresent scenario of small-sized sensors with limited power deployed in large numbers over an area to monitor different phenomenon. The sole motivation of a large portion of research efforts has been to maximize the lifetime of the network, where network lifetime is typically measured from the instant of deployment to the point when one of the nodes has expended its limited power source and becomes in-operational â€“ commonly referred as first node failure. Over the years, research has increasingly adopted ideas from wireless communications as well as embedded systems development in order to move this technology closer to realistic deployment scenarios. In such a rich research area as wireless sensor networks, it is difficult if not impossible to provide a comprehensive coverage of all relevant aspects. In this book, we hope to give the reader with a snapshot of some aspects of wireless sensor networks research that provides both a high level overview as well as detailed discussion on specific areas.