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We present a time synchronization scheme for wireless sensor networks that aims to conserve sensor battery power while maintaining network connectivity for as long as possible. The proposed method creates a hierarchical tree by flooding the sensor network from a designated source point. It then uses a hybrid algorithm derived from the Timing-sync Protocol for Sensor Networks (TSPN) and the Reference Broadcast Synchronization method (RBS) to periodically synchronize sensor clocks by minimizing the number of required transmissions.

In multi-hop ad-hoc networks, a depleted sensor will drop information from all other sensors that route data through it, decreasing the physical area being monitored by the network. It is therefore imperative that time synchronization schemes are aware of the number of sensors being used at any given time. The proposed method uses several techniques and thresholds to maintain network connectivity. A new source point is chosen when the current one's battery power reaches a designated energy threshold. The network is also re-flooded whenever the number of used sensors drops below another threshold.

We implement this new synchronization technique on Matlab and show that it can provide significant power savings over both TPSN and RBS; the power reduction is even more drastic in large multi-hop sensor networks. The method also improves upon these algorithms by maintaining a large area of coverage even when some sensors lose power.

Energy-Aware Synchronization in Wireless Sensor Networks

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1. Introduction

Time synchronization is a crucial aspect of any 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) [1] and the Network Time Protocol (NTP) [2]. These conventional networks are effective for communication of large amounts of data, typical of Internet and Local Area Networks (LANs).

1.1. *Wireless Sensor Network Overview*

Over the past few years, applications have been developed to monitor environmental properties such as temperature and humidity; they can also be used to analyze motion of animals or vehicles. One of the most important requirements for these monitoring applications is unobtrusiveness; this creates a need for wireless ad-hoc networks using very small sensing nodes. These special networks are called “wireless sensor networks” or WSNs. These networks 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. If an emergency arises, the network can relay the information to the city hall and notify police, fire, and ambulance drivers of congested streets. The sensors could even suggest the fastest route to the emergency area.

Another emergency condition could arise should a chemical plant be damaged and develop a leak, creating a toxic fume cloud that could endanger an entire city [3].

Sensors could be deployed from the safety of a plane above the cloud. As the sensors fall through the fumes, they could determine the size of the cloud, as well as the wind speed which propels the cloud. The sensors could then relay this information either to the plane or to a unit on the ground, which could then suggest evacuations according to the cloud's projected path. Changes in wind speed and direction could be detected from the plane above the cloud, so the projected path could be updated in real-time as well.

When compared to computer terminals in 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 [4]. 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 sending transmissions.

With the emergence of WSNs, current LAN synchronization methods will not work efficiently. GPS provides good synchronization accuracy, but requires a very large amount of power from the sensors. In a power-constrained sensor, this synchronization is infeasible. NTP is also infeasible since it is designed for traditional computer networks and will not scale well for wireless sensor networks. Some new synchronization methods have been developed specifically for sensor networks, such as the Timing-sync Protocol for Sensor Networks (TPSN) and the Reference Broadcast Synchronization method (RBS).

1.2. Objectives

RBS and TPSN both achieve accurate clock synchronization within a few microseconds of uncertainty. However, they are both designed for networks with a small number of sensors and are not specifically geared towards energy conservation; although these algorithms will work for larger networks, their energy consumption becomes inefficient and network connectivity is not maintained once nodes begin losing power. Simulating each of these methods shows that synchronizing a large sensor network requires an unnecessarily large number of transmissions, which will quickly deplete sensors and reduce the network's coverage area.

This work concentrates 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.

1.3. Organization

Chapter 2 explains wireless sensor networks in more detail. Applications for WSN time synchronization are listed. The proposed synchronization techniques require

proper routing, localization and other operations to be successful. Previous research in these areas is also outlined in this chapter.

Chapter 3 describes in detail how RBS and TPSN operate. Both of these algorithms provide high accuracy, but do not concentrate on energy efficiency in large multi-hop networks. This chapter will provide a benchmark to which the presented method can be compared to.

Chapter 4 discusses the details of the hybrid method. An efficient synchronization method is used depending on the number of receivers for each sensor. Once the source sensor's battery power drops below an established threshold, a new source node is chosen and the network is re-established. Assumptions will also be described in this chapter.

Chapter 5 presents the energy-consumption data and simulation results from our method. Our data is then compared to RBS and TPSN as tested in various network topologies.

Chapter 6 provides conclusions and summaries of the advantages of the hybrid method and comparisons to established sensor network synchronization methods. This chapter will also highlight future work that could be done to further improve upon power consumption.

The Matlab source code for all simulations is provided in the appendix.

2. Related Work in WSN

When wireless sensor networks were first being developed, the main topic of research involved reliability and routing. WSNs are usually deployed in relatively inaccessible environments such as heavily forested areas or within buildings, where using wired networks are impractical. Consequently, transmissions are unreliable and lost packets are common. Equation (2.1) shows how signal power fades as it travels further from the transmitter:

$$P_R = \frac{P_T}{d^c}, \quad (2.1)$$

where P_T is the power of the transmitted signal, d is the distance from the transmitter, and c is the path loss coefficient. These typical environments have large path loss coefficients because of signal fading from diffractions, reflections, and scattering off of walls and foliage. SCALE (Simple Connectivity Assessment in Lossy Environments) is a tool developed for Mica2 sensors to measure packet delivery [5]. Using SCALE, research has verified the above fading effects on sensor networks. It was shown that outdoor urban environments with large buildings disrupt wireless signals more so than do doors and walls from within buildings. Flooding algorithms such as the ones in [6] and [7] have been used to study multi-hop routing in WSNs. Unreliable networks have several issues that were uncovered with this algorithm:

- *Backward links*: a link that transmits flood packets back towards the source.
- *Long links*: a link that is significantly longer than would be expected given the transmission power level.

- *Stragglers*: sensors that do not receive flood packets, despite having a high probability of reception from a neighboring transmitter.
- *Clustering*: a node that connects to a very large number of receivers.

Span is an algorithm that reduces a network's energy consumption while maintaining its topology as well as its sensing effectiveness [8]. Each node determines whether it should sleep or become a coordinating node that forwards packets. This decision is based on an estimation of the number of neighbors that would benefit from the node's state. The network's lifetime increases as more nodes are deployed and as the sleep time for each node is increased.

ASCENT is another algorithm that changes the network's topology in an effort to maximize the lifetime of each sensor [9], [10]. In this case, each node will self-configure itself based upon its connectivity and its participation in the network's topology. Timers are used to switch a sensor's state between sleep, passive, test, and active. A sleeping sensor has its radio turned off to save power, while an active sensor has its radio on and communicates with its neighbors. A sensor in the test phase monitors the number of neighbors and its data loss rate to determine whether it is beneficial to join the network; if one of these parameters is not above a certain threshold, then the node will become passive, otherwise it will become active. A passive node will transition back to the test phase if the data loss rate is low, the number of neighbors is below a threshold, or if a help packet is received. If none of these parameters are met, the node goes to sleep and transitions back to the passive phase once a timer expires. When the thresholds and timer lengths are set correctly, ASCENT has reduced packet loss while decreasing energy

consumption. The algorithm must still be tested for large networks to determine its scalability.

One of the most common uses for wireless sensor networks is for localization and tracking. 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. Information-driven sensor query (IDSQ) is one tracking method that works well, even for multiple targets [11]. It defines a “belief state,” which contains the position and velocity of each target. Previous tracking methods scaled very poorly since every sensor would update its belief state, requiring a large amount of network communication. With IDSQ, only nodes that have useful and non-redundant information will have their belief state updated. Furthermore, IDSQ tracks multiple targets more efficiently by splitting up the network into sub-sections, each of which is assigned a leader node that keeps track of when objects enter and leave the area. Contour tracking at the boundaries can be accomplished by using triangulation and a contour threshold.

Sensor networks have also been used to monitor conservation habitats for wildlife [12], [13], [14]. Sensors are being used to monitor the nesting habits of a coastal bird on Great Duck Island, 10 miles off of the coast of Maine. In the past, researchers would have to go to the island and physically disrupt the nests to count eggs and to measure temperature and humidity. Now however, small sensors are able to do these same observations without disrupting the birds’ nesting habits.

Localization and tracking are also used when attempting to locate a sniper’s location from the gun’s muzzle blast [15]. Each sensor will detect the blast noise at unique times but within microseconds of each other, so the only way to accurately

compare observations is if all of the sensors are well-synchronized [16]. If the sensors know their locations relative to one another, then the path of the bullet can be reproduced from the observations of the blast noise, ultimately finding the point of origin.

Target tracking applications such as the ones just described require some degree of synchronization amongst nodes to provide useful observation comparisons. A significant distinction between each application is the degree of synchronization that is required; when tracking an animal or a vehicle, up to one millisecond of accuracy could be required, whereas in the case of sniper localization, the sensors must be synchronized to within a few microseconds. A high-accuracy algorithm will require more communication amongst nodes which will use more energy, whereas a less accurate method will usually require less energy. Some of the synchronization algorithms are discussed in Sections 2.1, 3.1, and 3.2.

2.1 *Traditional Time Synchronization Algorithms*

2.1.1 NTP

One of the first protocols used for computer systems is the Network Time Protocol (NTP), first developed in 1985. This protocol uses a relatively large amount of memory to store data for synchronization sources, authentication codes, monitoring options, and access options [17], [18]. As mentioned earlier, typical wireless sensor nodes have limited onboard memory; for example, Crossbow's popular Mica2 and Mica2DOT sensors each have 4KB of configurable memory. A large sensor network will require large files for synchronization sources and codes. Even 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 μ s in a LAN; these specifications are usually adequate for computer networks, but do not meet the requirements for most sensor network applications.

2.1.2 GPS

Global Positioning System (GPS) is another accurate and commonly used synchronization protocol. The Department of Defense began launching NAVSTAR (Navigation Signal Timing and Ranging) GPS satellites in 1978 to allow the U.S. military to localize any object on the ground to within a few feet [19]. Although commercial applications could use GPS when it was first created, the technology was classified so unauthorized users would have inaccurate results, usually to an accuracy of 100 meters at best. This technology was de-classified in 2000, leading to the development of commercial GPS navigation systems with the same accuracy as the military systems. The NAVSTAR GPS currently consists of 24 active satellites which continuously transmit their own position and a time code in the microwave spectrum at 1.5 GHz. By measuring the relative arrival times of signals from several satellites and using triangulation, a GPS receiver can determine its own position. The radio signals are electromagnetic waves traveling at the speed of light, so the propagation delay is only 50 ms from an altitude of 10,000 miles, so GPS's triangulation method requires very precise time information from the satellites. The master clock on each satellite is therefore kept within 1 μ s of the U.S. Naval Observatory's Master Clock [20], [21].

At first glance, GPS would seem to be an ideal candidate for time synchronization for wireless sensor networks since the algorithm is wireless and the local node clocks will always synchronize to 1 μ s of each other. However, there are a few requirements that GPS fails to meet. 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 [22]. These two traits counteract the goal of using small and mobile nodes to create a wireless sensor network. In addition, the GPS receiver draws 120 mA while the Mica2DOT wireless sensor only uses 25 mA when transmitting at maximum power. Lastly, signal attenuation from scattering and diffraction is significant since GPS operates at a high frequency, which forces the receiver to have an unobstructed view of a large portion of the sky to accurately receive the satellite signals. This line-of-sight requirement cripples GPS's use for sensor networks dispersed within a building or in a heavily forested area.

2.2 Media Access Control Issues

A significant amount of research has been done on the medium access control (MAC) layer. These protocols control how sensors access the radio channel to communicate with neighbors, so energy can be saved by using the channel more efficiently. Two of the classic MAC protocols are ALOHA [23] and CSMA (carrier-sense multiple access) [24]. In ALOHA, packets can either be transmitted immediately after they are generated or on the next available slot. Dropped packets from collisions are simply re-transmitted later. In CSMA, a sensor will listen to the MAC layer before it transmits a packet. This MAC protocol is currently being used in many wireless

technologies, including 802.11. Both of these protocols use energy very inefficiently, so new energy-aware modifications to the MAC layer have been created.

Packet collisions are one of the most wasteful phenomena in wireless communication, since these packets must be re-transmitted in full. One way to greatly reduce collisions is by using TDMA (time division multiple access), where each sensor would be given a unique time slot in which to transmit information. LEACH (Low-Energy Adaptive Clustering Hierarchy) is an application of TDMA towards wireless sensor networks [25]. It organizes nodes into clusters with one head node, and applies TDMA within each cluster. Bluetooth has a similar approach [26], using clusters called piconets, where devices are given the right to transmit only when their time slot becomes available. Since each sensor requires a unique transmission time slot, LEACH and other TDMA-type algorithms do not scale very well with larger networks. In addition, sensors are not allowed to directly communicate with each other, so very accurate time synchronization is required to ensure that one sensor's transmissions do not spill over into another sensor's time slot.

Instead of using TDMA, contention-based algorithms allow sensors to communicate directly with each other, removing the dependency on accurate time-synchronization. S-MAC is a modification to the MAC protocol designed specifically for WSNs to increase energy efficiency [27]. To do this, a low duty-cycle is first obtained by scheduling the nodes to transmit depending on their remaining battery life. When transmitting a packet, the S-MAC adds a duration field to notify other nodes how long of a packet transmission is needed. The nodes will therefore immediately know for how long they must refrain from sending their own data, even without requiring

synchronization. T-MAC improves upon S-MAC by adding the ability for a variable duty-cycle to compensate for inconsistent data rates [28].

3. WSN Time Synchronization Algorithms

Although traditional synchronization methods are effective for computer networks, they are ineffective in sensor networks. New synchronization algorithms specifically designed for wireless sensor networks have been developed and can be used for several applications.

3.1. RBS

Clearly GPS and NTP are not very effective in wireless sensor applications. One of 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 [29]. This algorithm defines the critical path, which is 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. RBS improves upon NTP by reducing the length of the critical path, which can improve the accuracy of the synchronization to $7 \mu\text{s}$ in light traffic. 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.

3.1.1. RBS Algorithm and Analysis

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; a set of nodes separated by 100 meters will have a propagation delay of 340 ns, 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. Also, 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.

The authors of RBS reported 11.2 μs for the synchronization error on the MICA2 wireless sensors. However, the motes have an integrated transmitter with a processor, requiring additional CPU cycles and yielding this relatively inaccurate precision (this

hypothesis was verified when RBS was tested using much more powerful IPAQs units, where the errors were 6.3 μs in light traffic and 8.4 μs in heavy traffic). By comparison, the errors for NTP using the IPAQs were 51 μs in light traffic and 1542 μs in heavy traffic. RBS clearly outperforms NTP, even on vastly inferior hardware.

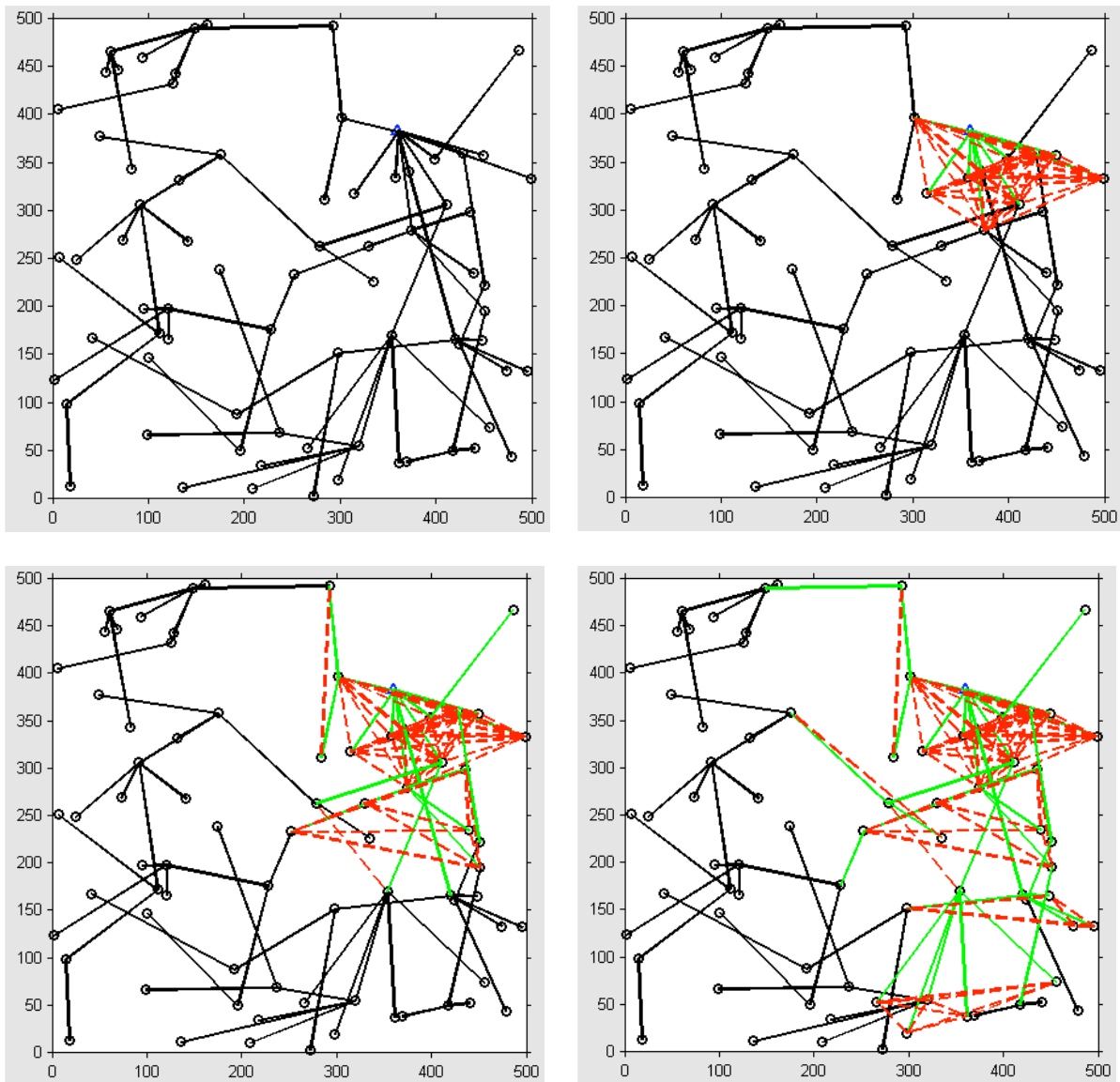
There are a couple of different implementations of RBS. The simplest method is designed for very high accuracy for sparse networks, where transmitters have at most two receivers. The transmitter can broadcast a synchronization request to the two receivers, which will record the times at which they receive 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. After 30 exchanges, the accuracy is improved from 11 μs to 1.6 μs .

The simplest 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 nondeterminism of the receiver, as well as clock skew. The receiver's nondeterminism 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.

Another important synchronization scenario is for multihop environments. 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 a bit more involved 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.

Figure 1 shows how a sensor network is synchronized by using RBS.



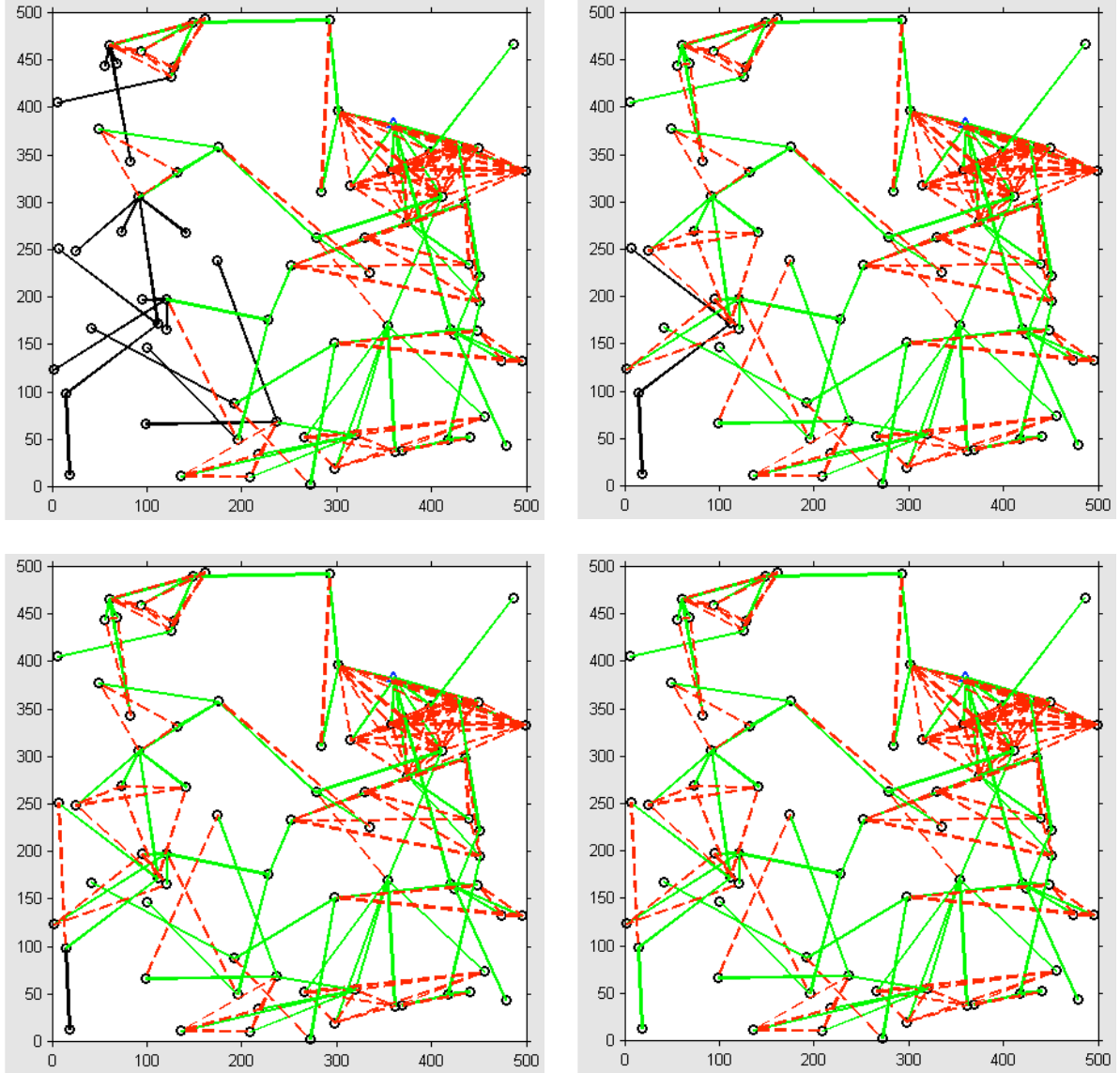


Figure 1: RBS Synchronization of a Wireless Sensor Network: the initial solid dark lines represent the network's topology after flooding; the solid light lines represent transmitter-to-receivers communication; the dashed lines represent receiver-to-receiver transmissions.

3.1.2. RBS Issues

There are a few issues with the RBS synchronization algorithm. 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 $O(n^2)$.

We have the following number of transmissions and receptions:

$$TX_{RBS} = n, \quad (3.1)$$

$$RX_{RBS} = n + \sum_{i=1}^{n-1} i = n + \frac{n(n-1)}{2} = \frac{n^2 + n}{2}. \quad (3.2)$$

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

Furthermore, RBS can be modified to multi-hop networks, but it remains mostly untested in this configuration. Larger sensor networks will require multi-hop routing for energy efficiency and redundancy.

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.

3.2. TPSN

The Timing-Sync Protocol for Sensor Networks (TSPN) was developed in 2003 in an attempt to further refine time synchronization beyond RBS's capabilities [30], [31]. 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 each bit to go 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.

3.2.1. TPSN Algorithm and Analysis

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. Given a parent node A and a child node B , node A sends a *synchronization_pulse* to B , timestamped at $T1$. Once node B receives the pulse, it timestamps at $T2$, then sends an *ack* packet back to A at $T3$. The parent node receives the *ack* packet and timestamps one last time at $T4$. These 4 timestamps provide estimates for clock drift (3.3) and propagation delay (3.4):

$$\Delta = \frac{(T2 - T1) - (T4 - T3)}{2}, \quad (3.3)$$

$$d = \frac{(T2 - T1) + (T4 - T3)}{2}. \quad (3.4)$$

The synchronization error can be calculated from the clock drift between the two nodes as well as the drift at $T4$:

$$Error = \Delta - D_{t4}^{A \rightarrow B}. \quad (3.5)$$

The following equations characterize $T2$ and $T4$:

$$T2 = T1 + S_A + P_{A \rightarrow B} + R_B + D_{t1}^{A \rightarrow B}, \quad (3.6)$$

$$T4 = T3 + S_B + P_{B \rightarrow A} + R_A + D_{t3}^{B \rightarrow A},$$

$$T4 \approx T3 + S_B + P_{B \rightarrow A} + R_A - D_{t4}^{A \rightarrow B}, \quad (3.7)$$

where S_A , $P_{A \rightarrow B}$, and R_B refer to the time to send the packet at node A (send time + access time + transmission time), the propagation time between nodes A and B , and the time to receive the packet at node B , respectively.

Equations (3.6) and (3.7) can be combined and used in (3.5) to get the theoretical error for TPSN:

$$Error_{TPSN} = \Delta - D_{t4}^{A \rightarrow B} = \frac{S^{UC}}{2} + \frac{P^{UC}}{2} + \frac{R^{UC}}{2} + \frac{RD_{t1 \rightarrow t4}^{A \rightarrow B}}{2}. \quad (3.8)$$

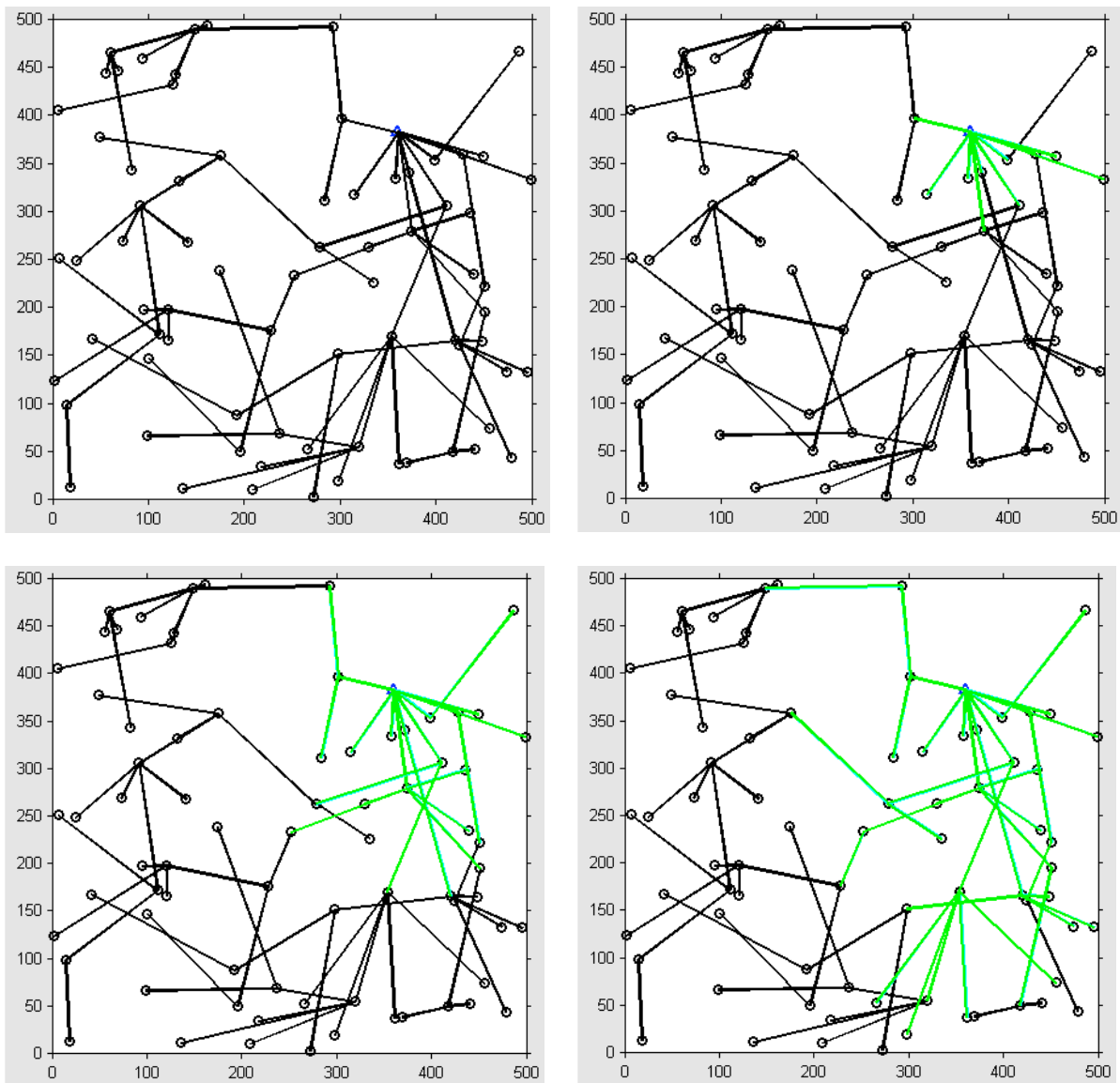
By contrast, the error for RBS as claimed by the TPSN authors is:

$$Error_{RBS} = \Delta - D_{t4}^{A \rightarrow B} = P_D^{UC} + R^{UC} + RD_{t1 \rightarrow t4}^{A \rightarrow B}. \quad (3.9)$$

In equations (3.8) and (3.9), S^{UC} , P^{UC} , and R^{UC} refer to the uncertainty in the send time, propagation time, and receive time respectively. RD is the relative drift between nodes A and B from time $T1$ through $T4$.

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 timestamping at the MAC layer just before the bits are sent through the transceiver.

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



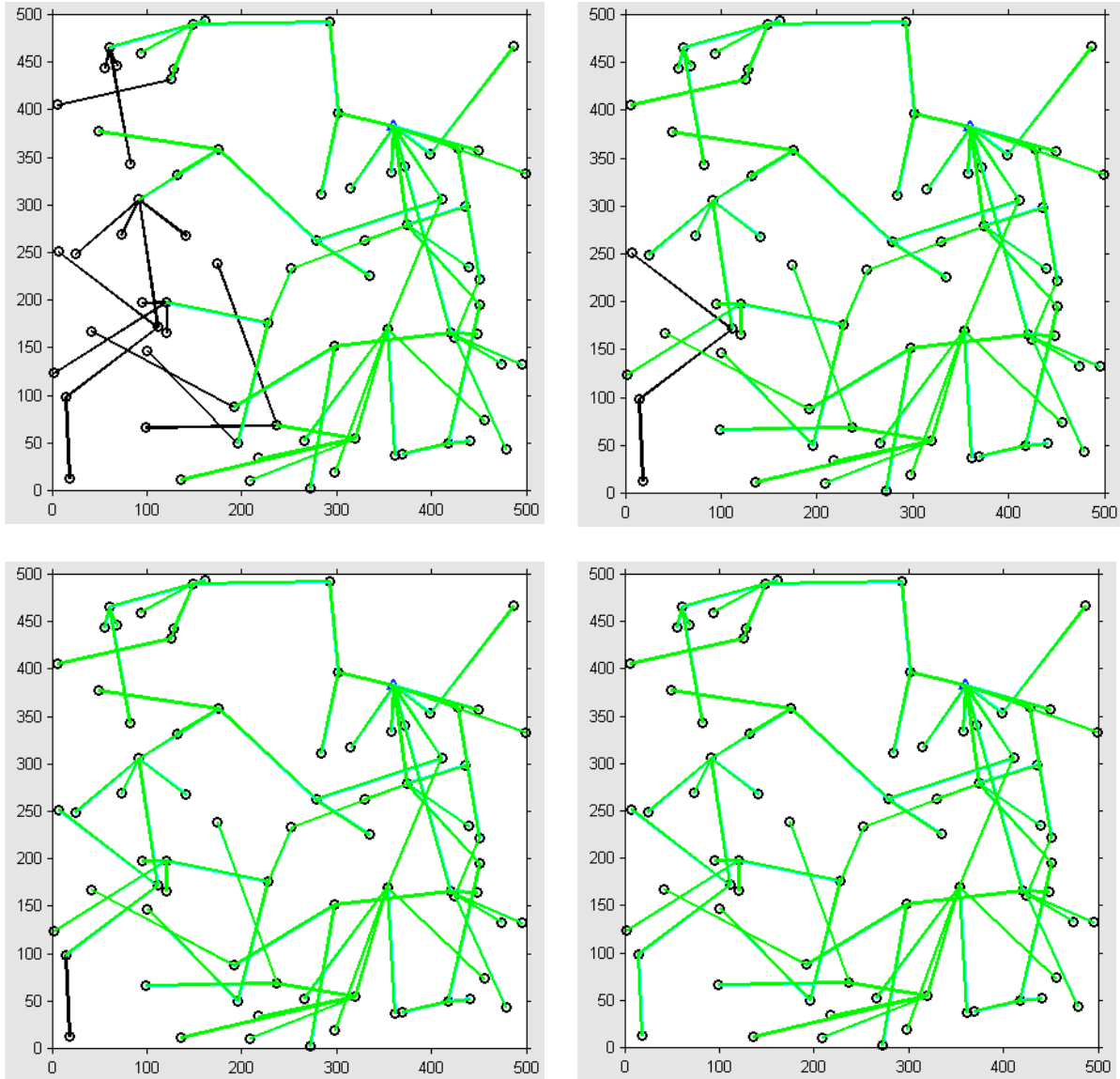


Figure 2: TPSN Synchronization of a Wireless Sensor Network: the initial solid dark lines represent the network's topology after flooding; the subsequent light lines represent successful transmitter-to-receiver synchronizations.

3.2.2. TPSN Issues

TPSN is a great improvement over RBS in terms of accuracy. Using a 2-way handshake reduces uncertainty in half since the average of the time differences is used.

The algorithm can be easily applied to multi-hop situations since it scales very well to dense networks:

$$TX_{TPSN} = n + 1, \quad (3.10)$$

$$RX_{TPSN} = 2n. \quad (3.11)$$

The main disadvantage that TPSN faces is its energy consumption in sparse networks; a 2-way handshake requires each node to receive a packet and to send one in response. For a parent node A with two children B and C , node A broadcasts the *level_discovery* packet, and then a *synchronization_pulse* packet. Nodes B and C receive both packets, and then transmit an *ack* packet back to node A . This example uses 4 transmissions and 4 receptions for TPSN. In contrast, the same situation would only require 2 transmissions and 3 receptions when using RBS; node A broadcasts a synchronization request packet with a timestamp, and then node B sends a second transmission to node C with its observation (node C can also transmit to node B with the same end result).

In addition, TPSN has the same problem as 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.

4. Energy-Aware Time Synchronization

The Timing-Sync Protocol for Sensor Networks (TPSN) and Reference Broadcast Synchronization (RBS) 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. As previously shown in (2.1), the signal's power decreases exponentially with distance and increases linearly with the transmitter's power. This means that a transmitter will have more children if it transmits at higher power or if the receivers have higher sensitivity to pick up weaker signals. These properties can be verified by building a network from uniformly distributed sensors and by changing the transmitter power or the reception power threshold, as shown in Figure 3.

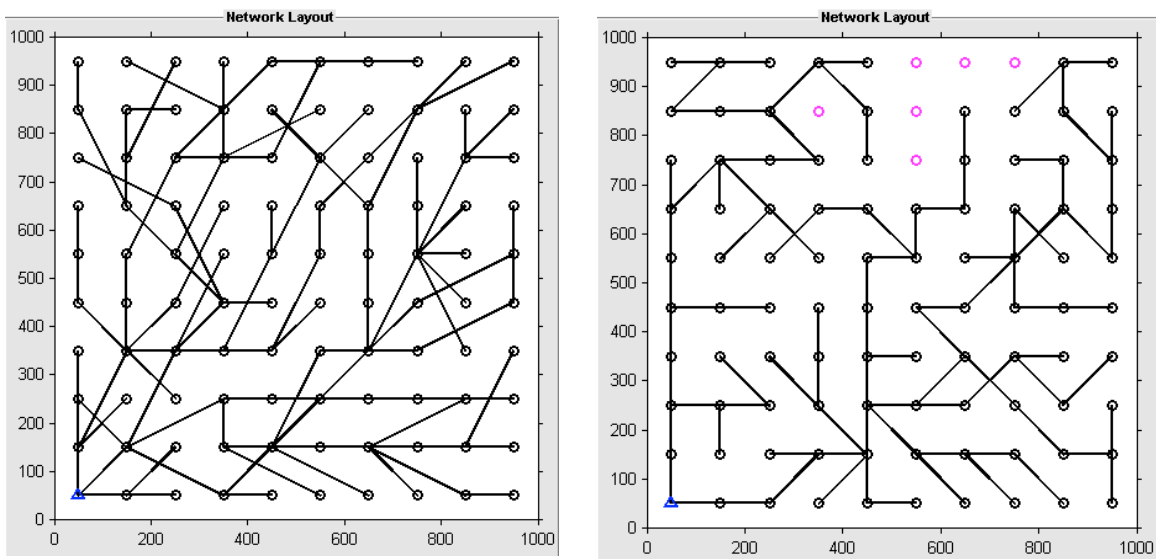


Figure 3: Uniformly distributed sensors with high transmission power (left) and with lower transmission power (right)

However, the sensors are most often randomly distributed and not uniformly spaced. Manually deploying sensors in a uniform grid is time-consuming and non-covert. Covertness is critical in battlefield and animal tracking scenarios. It would be best to drop the wireless sensors from an airplane to avoid disturbing the environment; however, the sensors would be distributed non-uniformly once they land. Even within buildings, WSNs are usually non-uniform; nodes can be distributed with uniform distances from each other, but the path loss is very variable in such an environment, mostly due to scattering. This property results in a large variance in the number of receivers for each transmitter, effectively creating a non-uniform sensor distribution. Figure 4 shows how power affects the flooding in a network with randomly distributed sensors.

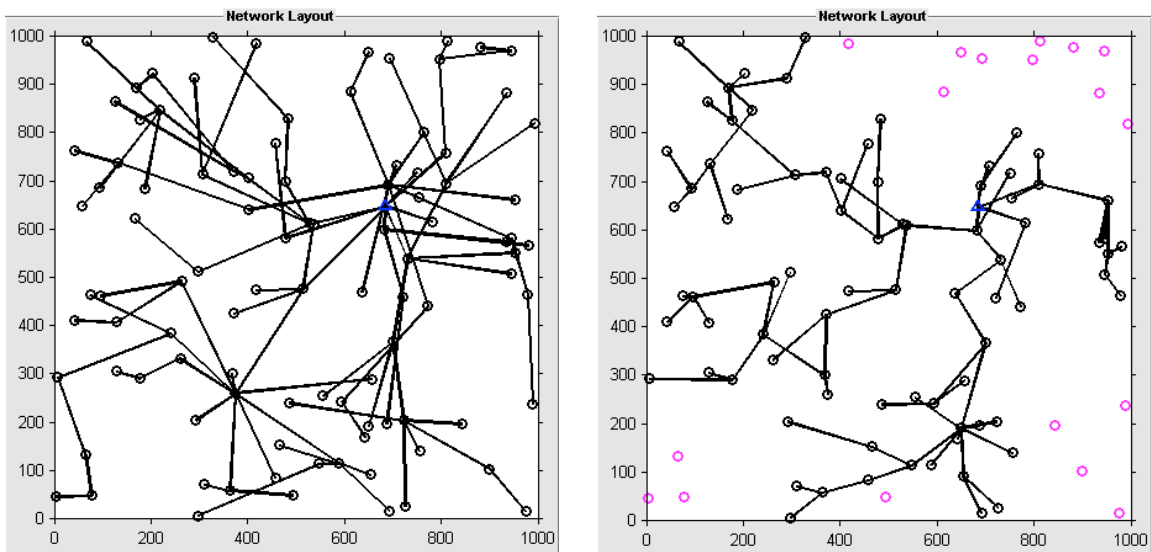


Figure 4: Randomly distributed sensors with high transmission power (left) and with lower transmission power (right)

The work presented in this thesis combines the efforts in various areas of research presented in the previous chapters to create a hybrid time synchronization algorithm that minimizes power usage by reducing the number of transmissions between sensors.

Although this method works for both uniform and non-uniform sensor deployment scenarios, many of the details are derived to best accommodate random sensor placement.

4.1. Hybrid Flooding

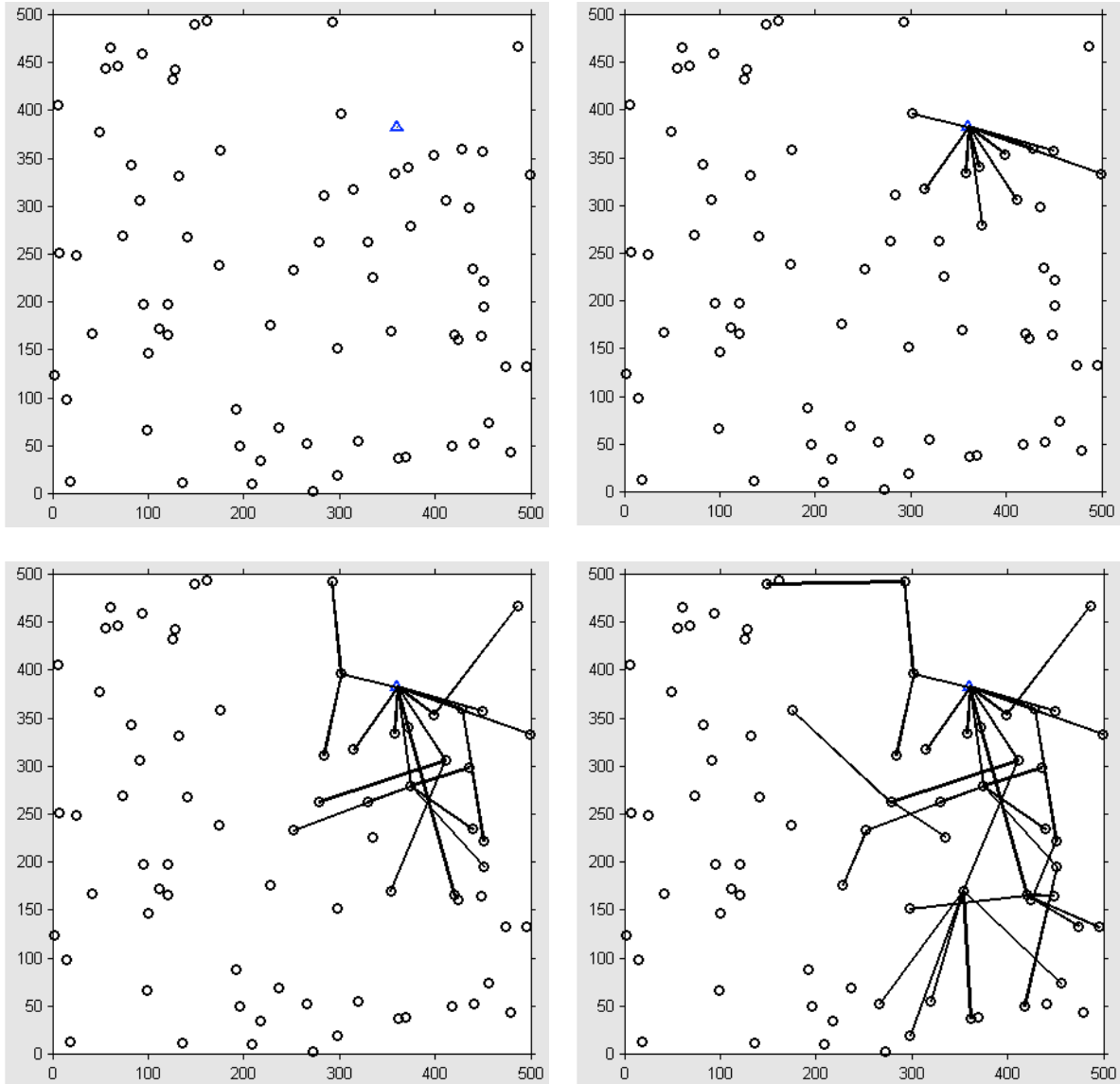
Before the sensors can be synchronized, a network topology must be created. Algorithm 1 is used by each sensor node to efficiently flood the network.

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
```

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. Figure 5 shows the implementation of Algorithm 1.



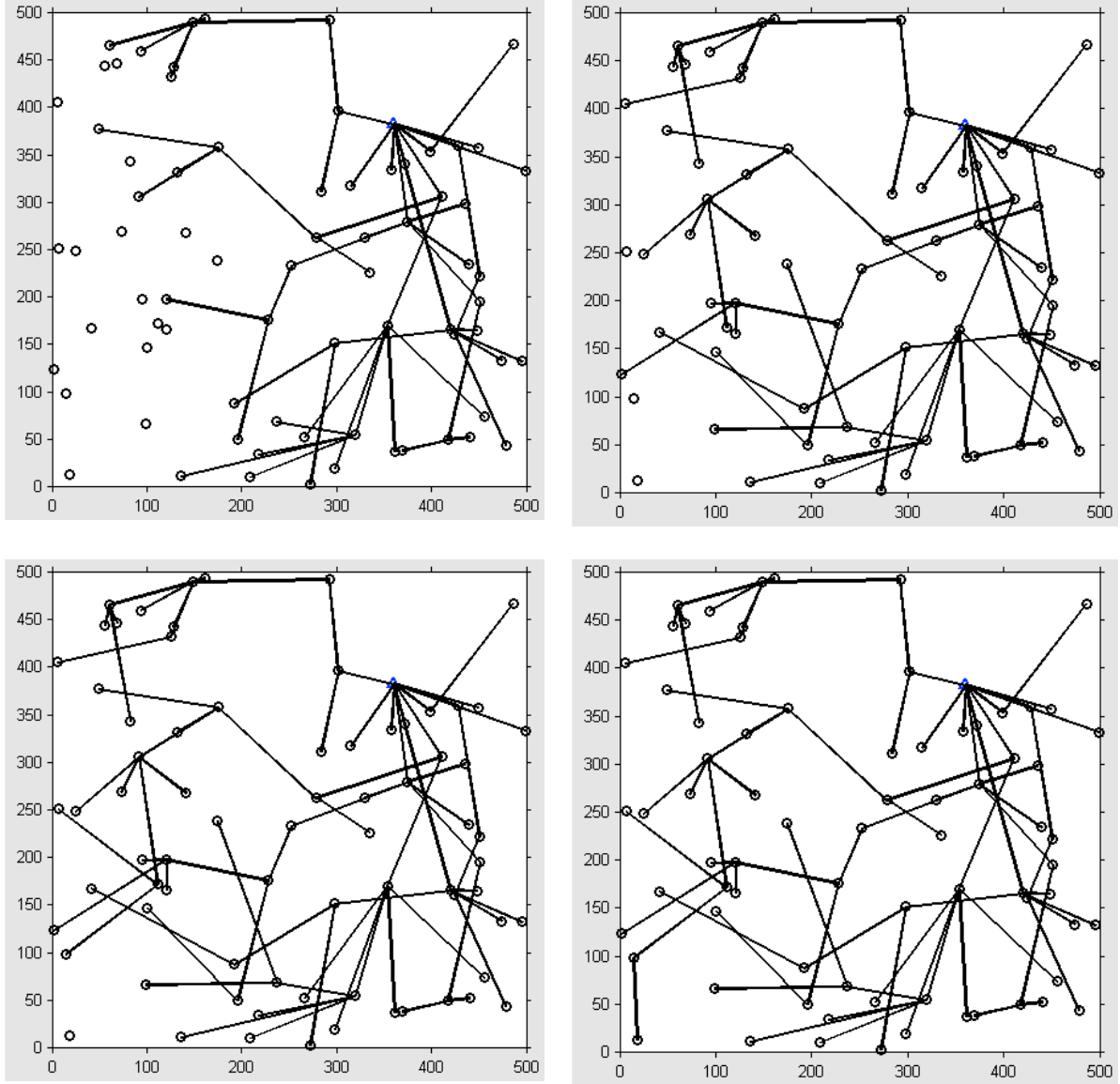


Figure 5: Flooding a Wireless Sensor Network: a *sync_req* packet is initially transmitted by the root node and is then re-transmitted by each receiver.

4.2. 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. As shown in Figure 4, 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 section 3.1, RBS excels when the transmitter has few receivers. In contrast, we showed that TPSN excels with many receivers per transmitter in section 3.2.

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. Equations (3.1), (3.2), (3.10), and (3.11) are combined below, where α is the ratio of reception-to-transmission power:

$$TX_{RBS} + \alpha \times RX_{RBS} = TX_{TPSN} + \alpha \times RX_{TPSN} . \quad (4.1)$$

For example, assume that a reception uses approximately half the power of a transmission, so $\alpha = 1/2$.

$$TX_{RBS} + \frac{1}{2} \times RX_{RBS} = TX_{TPSN} + \frac{1}{2} \times RX_{TPSN} , \quad (4.2)$$

$$n + \frac{1}{2} \left(\frac{n^2 + n}{2} \right) = n + 1 + \frac{1}{2} (2n) , \quad (4.3)$$

$$n + \frac{n^2 + n}{4} = 2n + 1 , \quad (4.4)$$

$$n^2 - 3n - 4 = 0 , \quad (4.5)$$

$$(n - 4)(n + 1) = 0 . \quad (4.6)$$

Equation (4.6) shows that the energies used by RBS and TPSN on this example platform are equal when there are 4 receivers per transmitter, so the *receiver_threshold* value from

the previous algorithm is set to 4 (negative values for *receiver_threshold* are not applicable here). With fewer than 4 receivers, the RBS algorithm is more efficient, while TPSN is better with more receivers. Since the ratio of reception-to-transmission power can vary for different platforms, the current draws for both reception and transmission are stored as variables and the *receiver_threshold* value is calculated at every sensor. This value is assumed to remain constant throughout the network. In general, we have the following equation to determine the *receiver_threshold*:

$$n^2 - 3n - \frac{2}{\alpha} = 0. \quad (4.7)$$

Algorithm 2 describes the algorithm used for the hybrid algorithm.

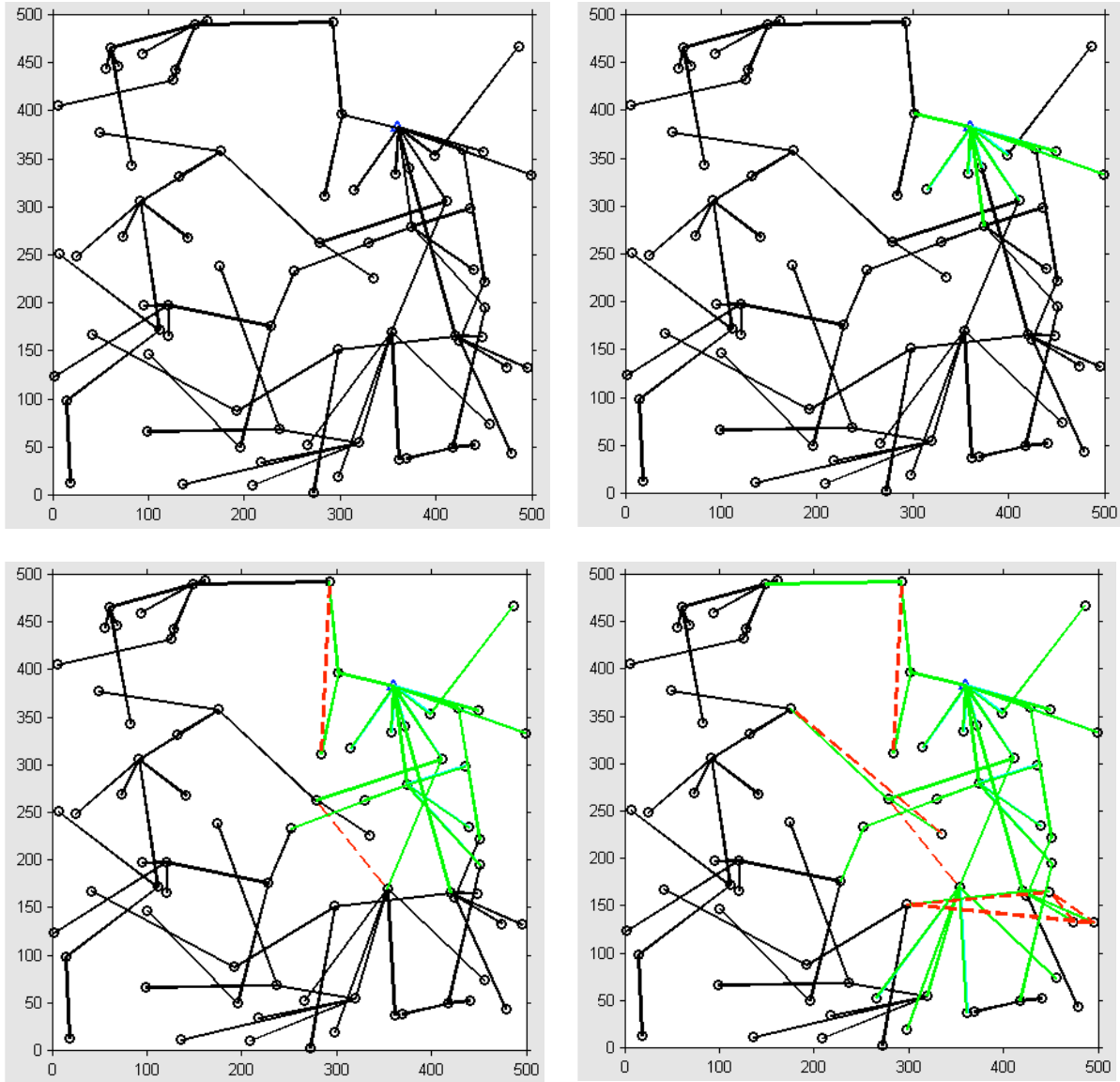
Algorithm 2: Hybrid Synchronization Algorithm

```

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

```

Figure 6 shows the implementation of Algorithm 2 in a wireless sensor network which has already been flooded.



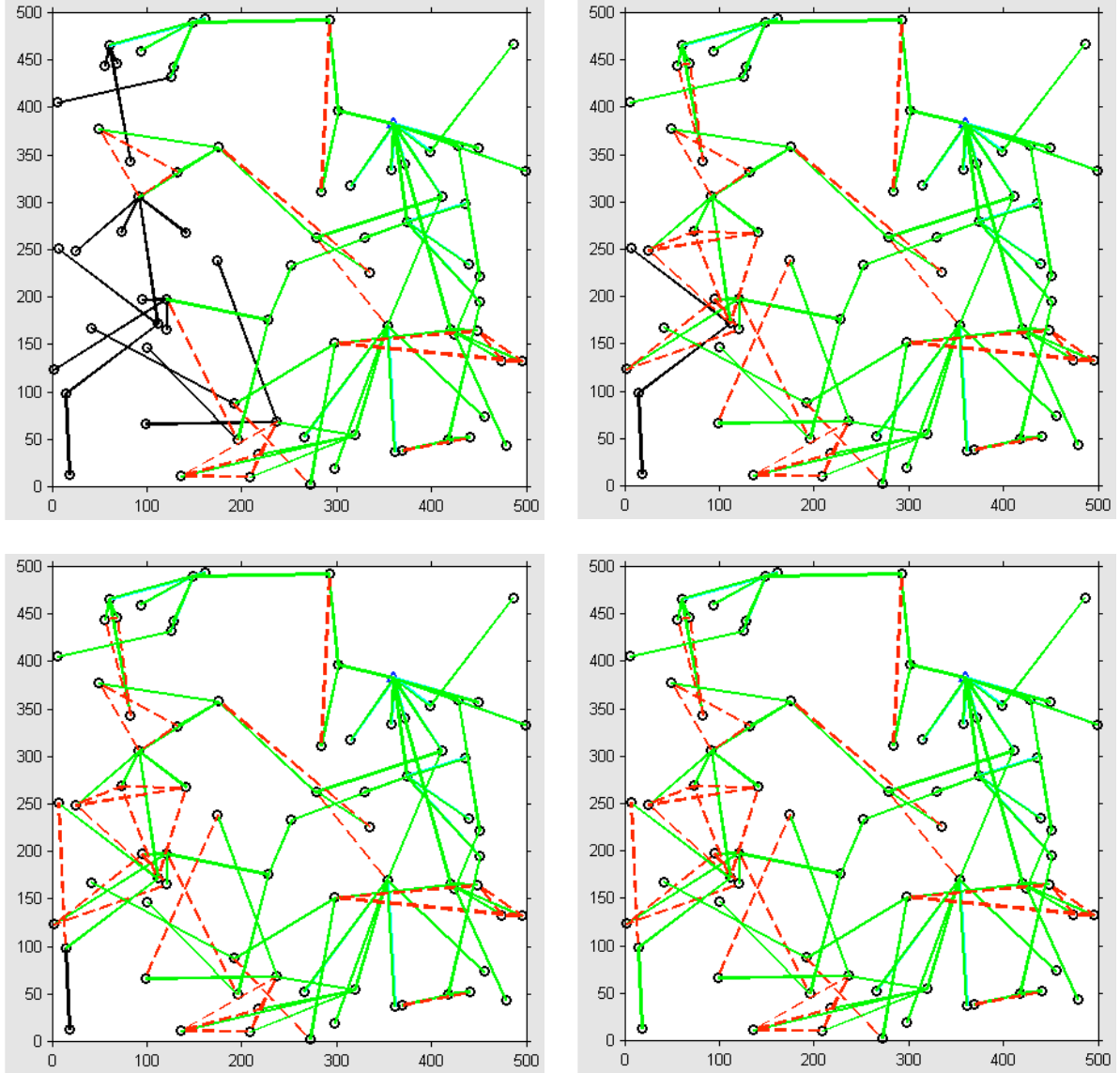


Figure 6: Hybrid Synchronization of a Wireless Sensor Network: the initial solid dark lines represent the network's topology after flooding; the solid light lines represent transmitter-to-receivers communication; the dashed lines represent receiver-to-receiver transmissions.

4.3. 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 according using the flooding algorithm described earlier in this section. 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 Algorithm 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
```

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.

5. Results and Analysis

Several simulations were run to compare the power consumption of the Timing-Sync Protocol for Sensor Networks (TSPN), the Reference Broadcast Synchronization (RBS), and the hybrid algorithm developed in chapter 4.

5.1. Hybrid Algorithm Validation

The first set of simulations were run to validate (4.7), which is the basis for the hybrid algorithm's behavior. Using this equation, a transmitting sensor can dynamically switch between RBS and TPSN by simply comparing the number of connected receivers to the reception/transmission power ratio. In this experiment, this ratio is changed in order to observe how each of the algorithms is affected. All other parameters are kept constant: 20 simulations are run over 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 [4], so:

$$\alpha = \frac{24}{75} = 0.32 \quad (5.1)$$

We can solve (4.7) with this value for α to get:

$$n^2 - 3n - \frac{2}{\frac{24}{75}} = n^2 - 3n - \frac{25}{4} = 0 \quad (5.2)$$

$$n = \frac{3 + \sqrt{9 + 25}}{2} \approx 4.42 \quad (5.3)$$

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. Figure 7 illustrates how changes in the *receiver_threshold* value affect the hybrid algorithm.

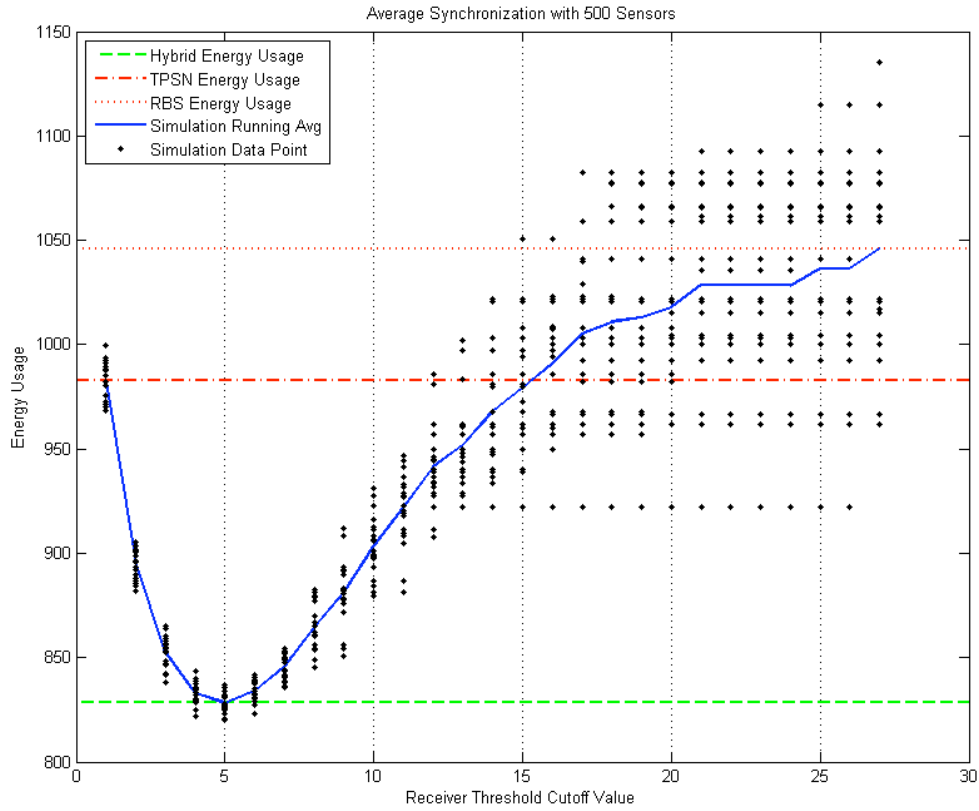


Figure 7: Mica2DOT Synchronization Comparison

The energy consumption from the hybrid algorithm when using the optimal *receiver_threshold* value is lower than both TPSN and RBS. As expected from (5.3), 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, as shown in Algorithm 2. 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, so this algorithm will consume the same amount of energy as the hybrid one.

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 [32], so:

$$\alpha = \frac{59.1}{42} \approx 1.407 \quad (5.4)$$

Solving equation (4.7) just as before, we get the following *receiver_threshold* value:

$$n \approx 3.42 \quad (5.5)$$

Not only does the MicaZ platform have a higher α value, it actually uses more power to receive information than to transmit it. In order to minimize energy consumption, the hybrid algorithm will automatically adjust the sensors so that any transmitter with 3 or fewer receivers will use RBS, while those with 4 or more receivers will use TPSN. Figure 8 shows the hybrid algorithm's performance when using the MicaZ platform.

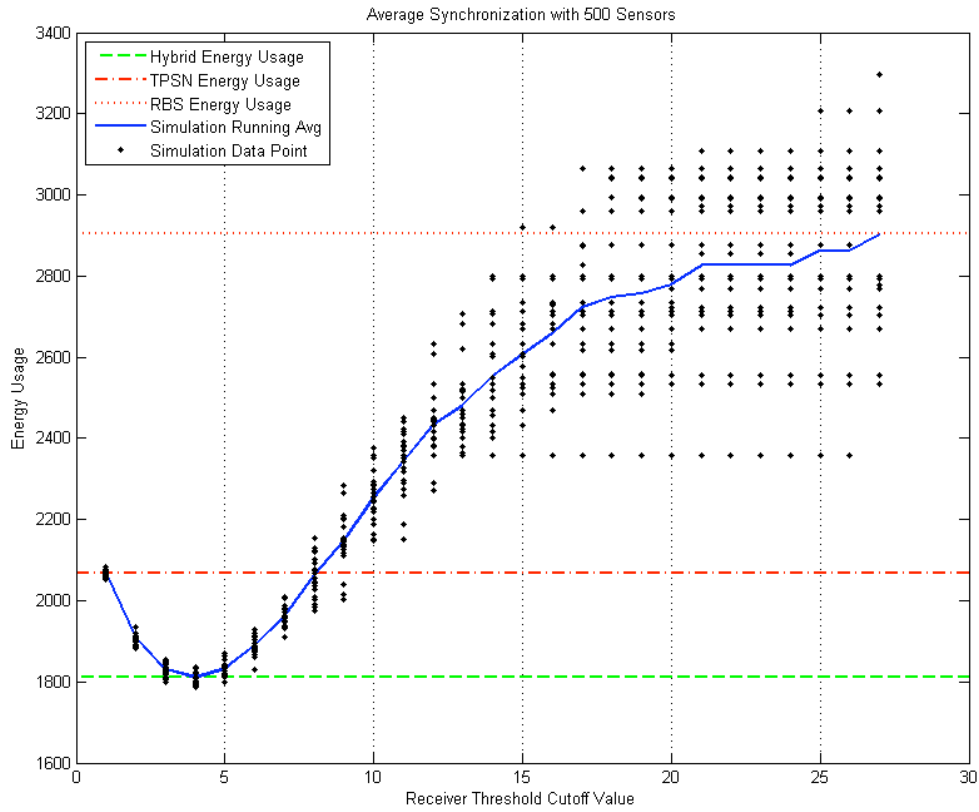


Figure 8: MicaZ Synchronization Comparison

When using MicaZ, the optimal *receiver_threshold* value is 3.42. This property is reflected in the above graph, where the local minimum has shifted further to the left when compared to the Mica2DOT platform.

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. The reception/transmission power ratio now becomes:

$$\alpha = \frac{8}{75} \approx 0.107 \quad (5.6)$$

The optimal *receiver_threshold* value now becomes:

$$n \approx 6.08 \tag{5.7}$$

Figure 9 illustrates the energy usage when the *receiver_threshold* changes.

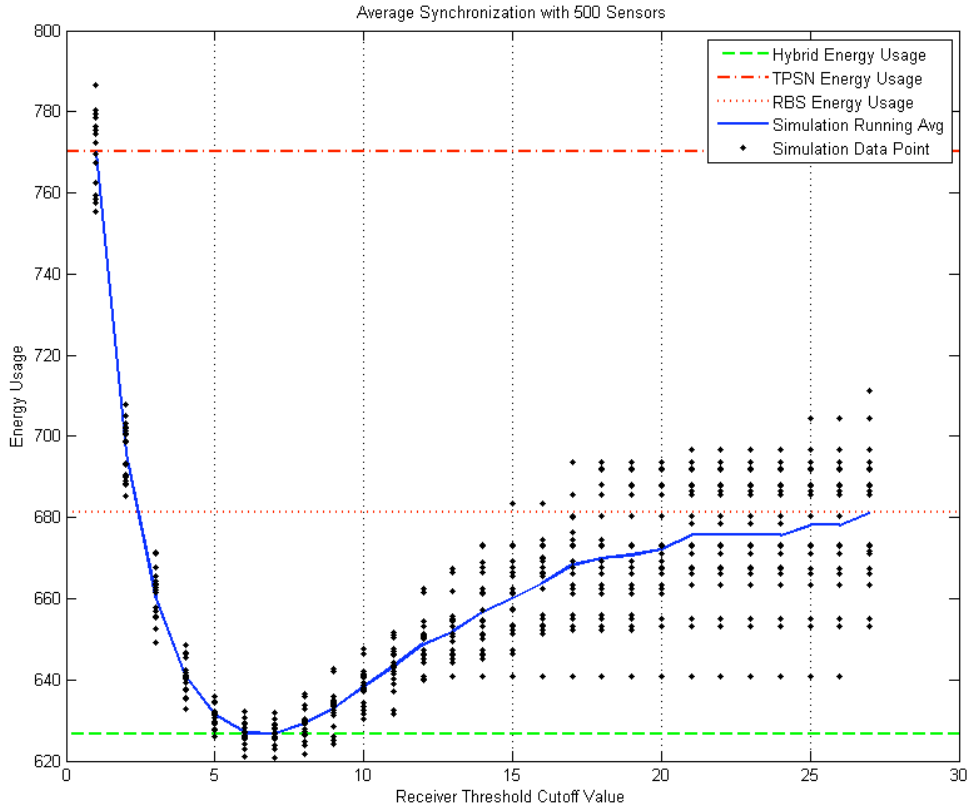


Figure 9: Synchronization Comparison for Architecture with $n=6$

In this example architecture, 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.

Another example would be an architecture which uses 75 mW for transmitting and 2 mW for receiving, so $\alpha=0.0267$ and $n=10.29$. This new threshold will move the graph's local minimum further to the right, as shown in Figure 10.

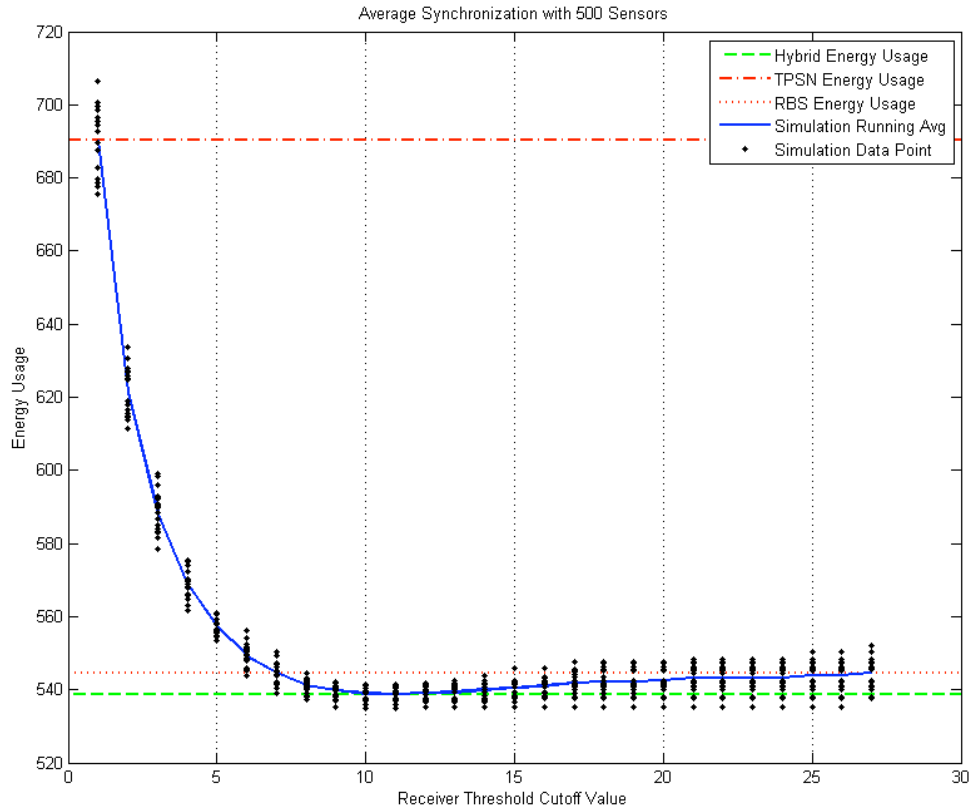


Figure 10: Synchronization Comparison for Architecture with $n=10$

Once again, the hybrid algorithm correctly predicts the minimum for energy consumption.

5.2. Synchronization Power Reduction

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.

Table 1: Average Number of Transmissions

Sensors	250	500	750	1000	1250	1500
RBS	249	499	749	999	1249	1499
TPSN	351	664	955	1245	1531	1810
Hybrid	261	533	800	1065	1331	1593
RBS Savings	-5.06 %	-6.76 %	-6.84 %	-6.59 %	-6.59 %	-6.26 %
TPSN Savings	25.58 %	19.72 %	16.20 %	14.50 %	13.06 %	12.01 %

Table 1 shows that RBS requires the fewest number of transmissions, while TPSN uses the most. The results for RBS and for TPSN both increase linearly with network size, as was expected from (3.1) and (3.10), respectively. The hybrid algorithm is up to 6.8% less efficient than RBS. However, when compared to TPSN, the hybrid algorithm performs very well. For small networks, there is up to a 25% savings in energy. As the number of sensors is increased, the hybrid algorithm efficiency drops to a 12% advantage over TPSN.

Table 2 shows the standard deviation in the number of transmissions for each of the synchronization algorithms. These results are important in determining how sensitive an algorithm is to modifications in the network's topology and sensor density.

Table 2: Standard Deviation for Transmissions

Sensors	250	500	750	1000	1250	1500
RBS	0.37 0.15%	0.00 0.00 %	0.00 0.00 %	0.00 0.00 %	0.00 0.00 %	0.00 0.00 %
TPSN	7.59 2.16 %	8.88 1.34 %	14.31 1.50 %	14.48 1.16 %	18.22 1.19 %	22.09 1.22 %
Hybrid	1.61 0.61 %	2.29 0.43 %	1.89 0.24 %	5.02 0.47 %	4.29 0.32 %	4.24 0.27 %

It is interesting to note that the standard deviation for RBS transmissions is usually 0, which shows that the number of transmissions is strictly dependent on the number of sensors in a network, regardless of network topology. The only exception occurred when 250 sensors were used, and was most likely caused when some sensors that did not receive a *flood_packet* and were therefore not used for synchronization.

The table shows that there is very little variation in the number of transmissions for TPSN. In fact, the largest standard deviation for TPSN comes from smaller networks. Similar results appeared when the hybrid algorithm was simulated, but with even less variability. Both of these algorithms are therefore only slightly affected by changes in sensor placement and sensor density.

Table 3 shows results for the number of receptions when using each of the algorithms.

Table 3: Average Number of Receptions

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 %

Here, we note that although the number of receptions when using TPSN increases linearly with network size, as would be expected from (3.11), they increase much more

quickly when using RBS, as illustrated in (3.2). 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. In contrast, the hybrid algorithm has a large advantage over TPSN in small networks, but that advantage decreases as more sensors are added.

Table 1 and Table 3 both show that the hybrid algorithm mimics RBS’s behavior for small networks. However, the hybrid algorithm changes its behavior as more sensors are included and begins resembling TPSN for very large networks.

Table 4 shows the standard deviation in the number of receptions for each of the synchronization algorithms. Similar to Table 2, these results help to determine how sensitive an algorithm is to modifications in the network’s topology and sensor density.

Table 4: Standard Deviation for Receptions

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 %

The table 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. Just as before, 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.

It is important to compare the number of transmissions and receptions amongst algorithms to understand each one's advantages and drawbacks, but the ultimate goal in these experiments is to minimize the total amount of energy expended when synchronizing the network. Since the transmitted packets are the same size for every algorithm, the radio and processor will be operating for a constant length of time, so the energy consumption can be calculated as follows:

$$energy = numTx + \alpha \times numRx . \quad (5.8)$$

Table 5 compares the energy values amongst algorithms.

Table 5: Average Energy Consumption

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 2 shows that all of the standard deviations for transmissions are relatively low, while RBS usually has a constant number. In contrast, Table 4 shows that while the standard deviations for receptions when using RBS are very high, TPSN usually has a constant number of receptions. Finally, Table 6 compares the standard deviation for each of the algorithms.

Table 6: Standard Deviation of Energy Consumption

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%

Although the standard deviations usually fluctuate with network size, larger networks generally increase the variance in RBS while decreasing the variance in TPSN. Furthermore, the deviation for RBS is relatively large, while that for TPSN is much lower. However, the variance for the hybrid algorithm is always lower than the other two, and it constantly decreases with larger networks.

These results show that not only is RBS's energy consumption highly dependent on network topology, it becomes even more so as the network becomes larger. In contrast, TPSN and the hybrid algorithm are less affected by the network layout, and both become even more independent as more sensors are introduced into a given area. The graphs below show how the energy consumption of all three algorithms compares with various network sizes.

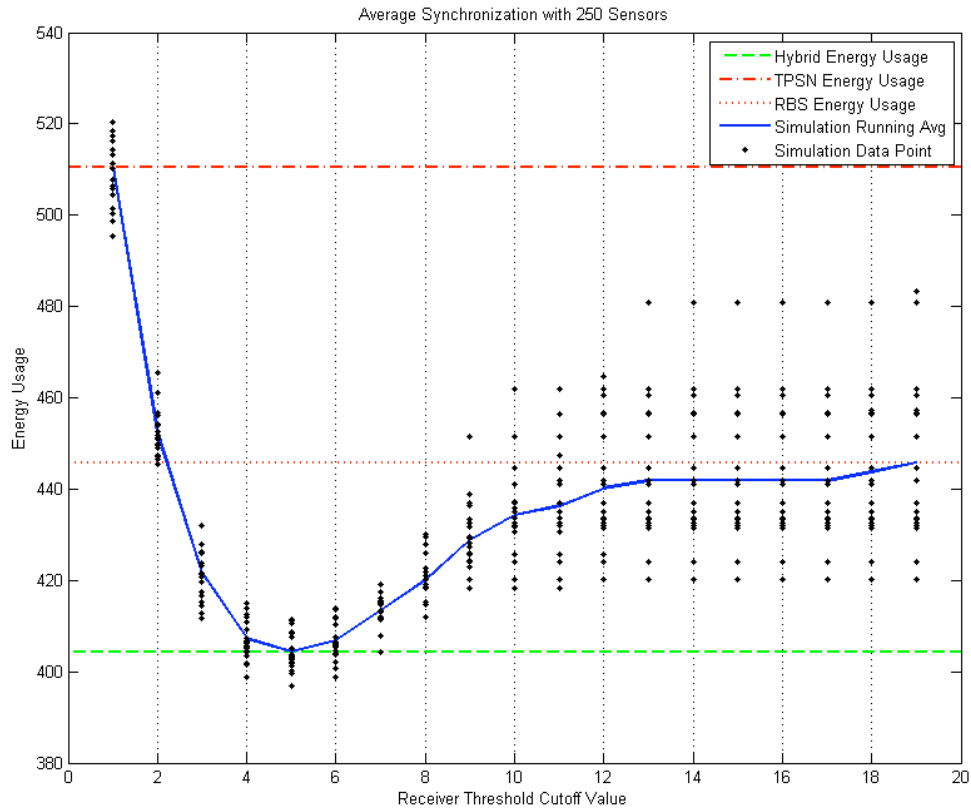


Figure 11: Synchronization Comparison for 250 Sensors

As mentioned before, the hybrid algorithm can adapt accordingly to transmission and reception power usages. TPSN and RBS become special cases of the algorithm. A *receiver_threshold* value of 1 will force a transmitter to use TPSN, whereas a *receiver_threshold* set to the largest number of receivers connected to a transmitter will force a transmitter to use RBS. These traits are shown in Figure 11.

For a relatively small network of 250 sensors, TPSN is the most inefficient algorithm of the three used in this study, followed by RBS. The hybrid algorithm outperforms TPSN by over 20%, while outperforming RBS by over 9%, as shown in Table 5.

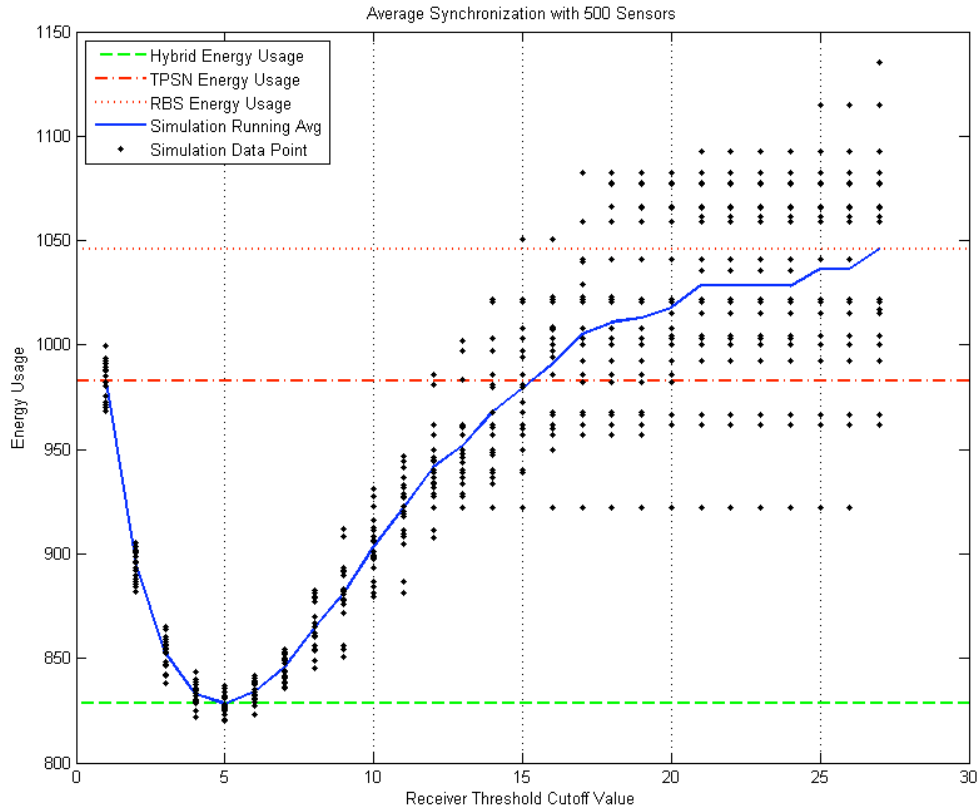


Figure 12: Synchronization Comparison for 500 Sensors

One major difference observed when the network grows from 250 sensors to 500 sensors is that RBS becomes less energy efficient than TPSN. The hybrid algorithm outperforms TPSN by 15.7%, while outperforming RBS by 20.8%.

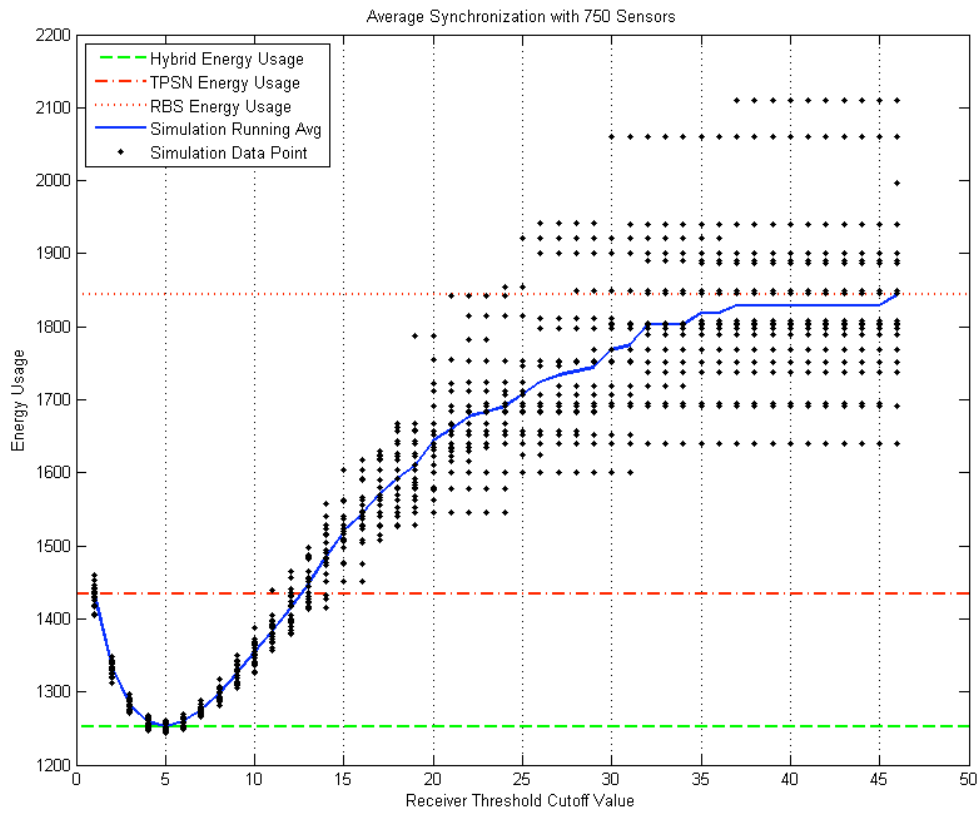


Figure 13: Synchronization Comparison for 750 Sensors

Once the network grows 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%.

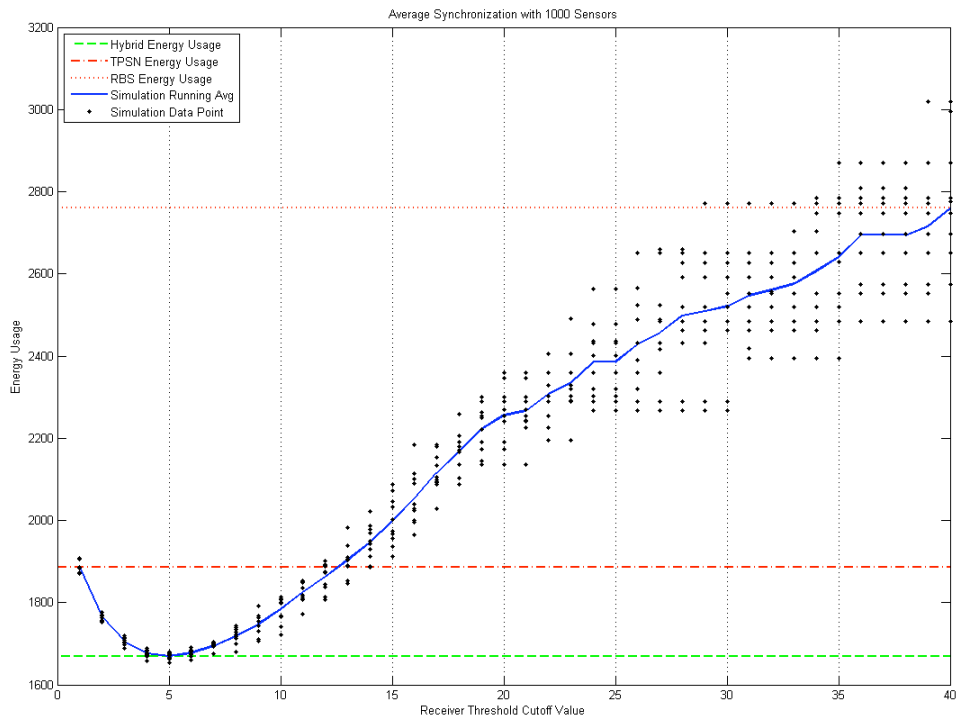


Figure 14: Synchronization Comparison for 1000 Sensors

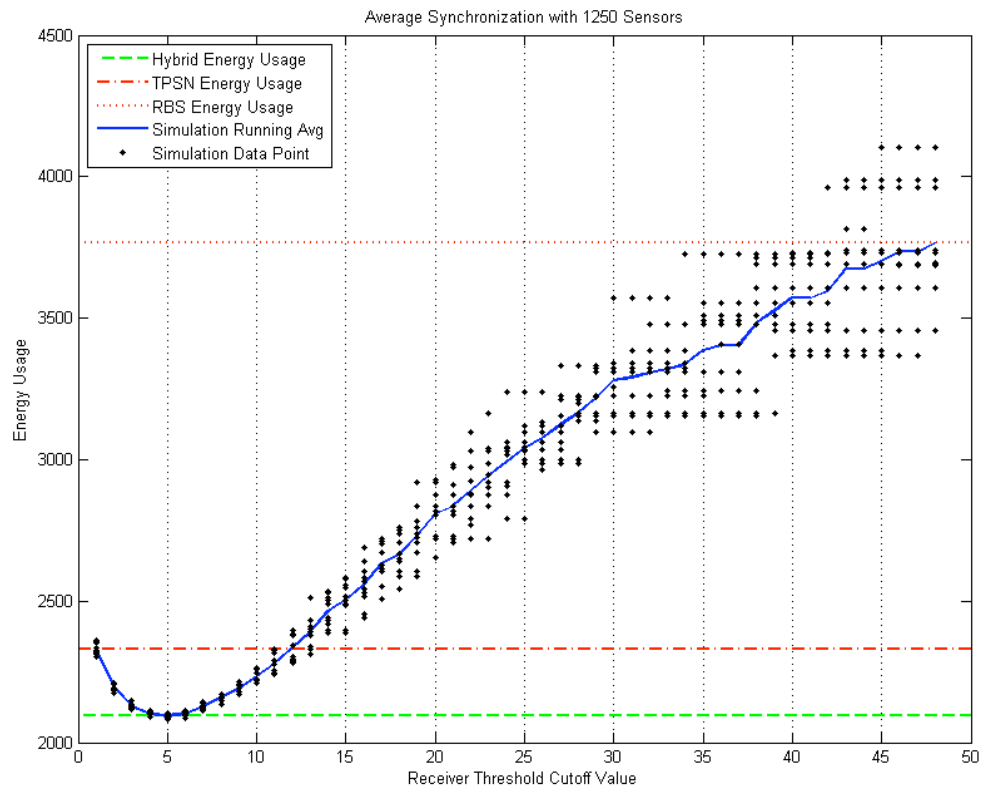


Figure 15: Synchronization Comparison for 1250 Sensors

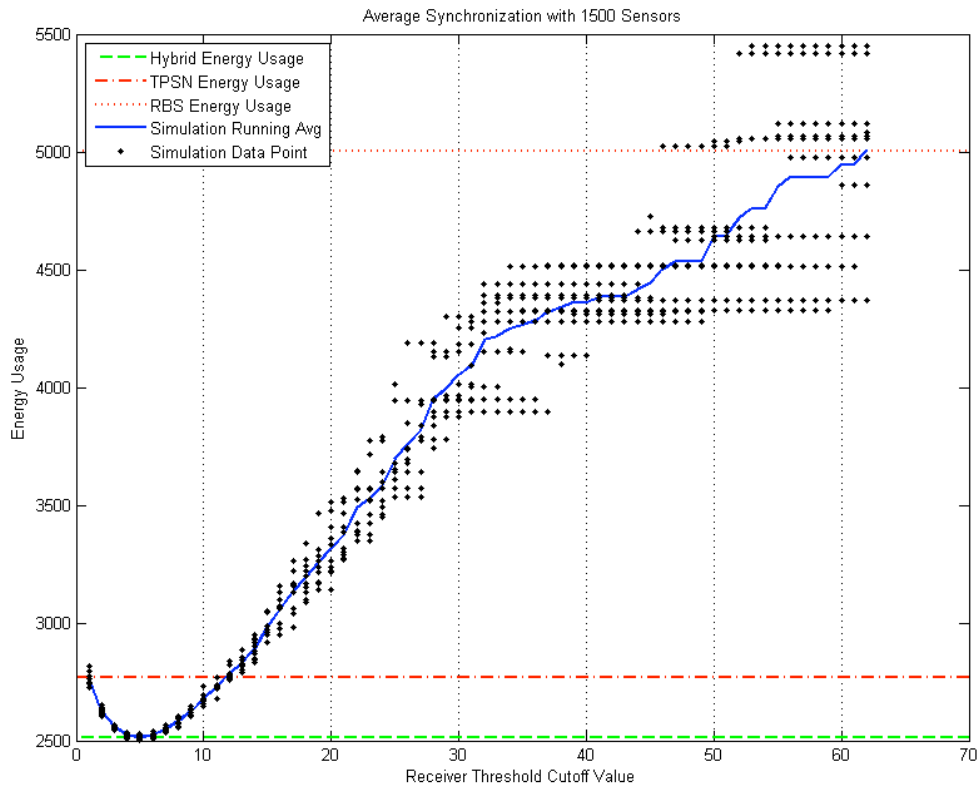


Figure 16: Synchronization Comparison for 1500 Sensors

As more sensors are introduced into the network, RBS becomes dramatically less feasible for a wireless sensor network. As shown in Table 5, 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 difference is 11% with 1000 sensors and 9% with 1500 sensors.

6. Conclusions

6.1. Summary

Wireless sensor networks have tremendous advantages for monitoring object movement and environmental properties; their small size makes them very stealthy and ideal for covert observations. Their size also makes it easy to drop them into a designated area by plane. Sensors can be deployed within a congested city to monitor traffic patterns. They can be used to monitor the migration patterns of animals. Should a chemical plant begin leaking toxic fumes, wireless sensors can monitor the movement and size of the fume cloud. They can also be deployed within a city or battlefield and can determine the location of a sniper from a rifle's blast noise.

All of these applications require some degree of synchronization to achieve the best results. Tracking animal movement does not require a high degree of accuracy, so the synchronization between clocks can be kept within a second. Monitoring traffic patterns or the movement of a toxic chemical cloud may be more challenging since the speed can change depending on congestion or on winds. Despite this uncertainty, a few microseconds of accuracy would be sufficient for either of these scenarios. Determining a bullet's point of origin from a rifle blast, however, is much more challenging. The blast will propagate uniformly from the sniper's location, so sensors closest to the shot will detect the shock wave first, while those further away will detect it later. To accurately determine the point of origin, the sensor clocks should be synchronized within a few microseconds of each other. The work developed in this thesis not only includes an

algorithm for synchronizing each sensor, but also includes algorithms for flooding and electing a new root node when the current root's battery is depleted.

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 km² 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 down to 0.3% as more sensors are used.

6.2. Future Work

There are a few improvements that can be implemented to the hybrid system in order to further decrease energy consumption.

- **Physical implementation:** although the system is designed from algorithms that have been researched and implemented on physical sensors, the work presented in this study has only been simulated using Matlab. Physically testing an algorithm on a sensor network comprised of 1500 sensors is a very difficult task; even testing a network with 250 sensors is not an easy feat. A study should be conducted to ensure that the algorithms developed in chapter 4 work correctly.
- **Localized re-flooding:** in the hybrid algorithm presented in this study, the entire network is re-flooded once the percentage of unused sensors reaches a given threshold. This threshold value is important since energy is wasted if the network topology is continuously updated whenever a sensor's battery dies. At the same time, the physical area being monitored decreases as the algorithm waits for the threshold value to be met. The best way to maintain network connectivity while using the least amount of energy is to re-flood only some areas of the network instead of the entire WSN. The hybrid algorithm is well-suited for localized floods since each transmitting sensor knows its receivers; when one of its receivers loses power, the transmitter can send a localized flood packet to re-establish the network's topology without disrupting the rest of the WSN.

- **Non-uniform path loss coefficient:** the research conducted here assumes that the path loss coefficient remains constant over the entire monitored area. This assumption may be valid in the case where sensors are dropped from a plane into a dangerous chemical cloud, but the path loss coefficient can drastically change in urban and heavily forested areas. When simulating a WSN that will monitor traffic patterns in an area surrounded by tall glass buildings, deflections and refractions will change the path loss coefficient; the only way to accurately portray this behavior in a simulation is to allow for a variance in path loss.
- **Network layer modifications:** sensor networks are quite different from the typical computer network being used today. The 5-layer internet architecture has been adapted to work with wireless sensor networks, but should be modified as it can be inefficient. Experiments should be conducted to find the best applicable network layer for sensor networks.

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