# A New Distributed Slot Assignment Algorithm for Wireless Sensor Network Under Convergecast Data Traffic

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*Abstract:* **The scarcest resource for most of the wireless sensor networks (WSNs) is energy and one of the major factors in energy consumption for WSNs is due to communication. Not only transmission but also reception is the source of energy consumption. The lore to decrease energy consumption is to turn off radio circuit when it is not needed. This is why TDMA has advantages over contention based methods. Time slot assignment algorithm is an essential part of TDMA based systems. Although centralized time slot assignment protocols are preferred in many WSNs, centralized approach is not scalable. In this paper, a new energy efficient and delay sensitive distributed time slot assignment algorithm (DTSM) is proposed for sensor networks under convergecast traffic pattern. DTSM which is developed as part of the military monitory (MILMON) system introduced in [27], aims to operate with low delay and low energy. Instead of collision based periods, it assigns slots by the help of tiny request slots. While traditional slot assignment algorithms do not allow assigning the same slot within two hop neighbors, because of the hidden node problem, DTSM can assign, if assignment is suitable for convergecast traffic. Simulation results have shown that delay and energy consumption performance of DTSM is superior to FPRP, DRAND, and TRAMA which are the most known distributed slot assignment protocols for WSNs or ad hoc networks. Although DTSM has somewhat long execution time, its scalability characteristic may provide application specific time durations.**

*Index terms*: **wireless sensor network, distributed slot assignment, TDMA, energy efficiency, delay.**

## I. INTRODUCTION

Developments in micro-electro-mechanical systems (MEMS) technology have enabled to integrate battery operated sensor, computational power and wireless communication components into a small size, low cost device [1, 2]. These tiny sensor nodes, which consist of sensing, data processing, and communication components, leverage the idea of sensor networks based on collaborative effort of a large number of nodes [3]. Sensor nodes carry limited, generally irreplaceable power sources. This is why energy efficiency is the most important factor in most of the sensor networks. Dominant factor in energy consumption for sensor nodes is communication [4].

The most common way to reduce energy consumption is to turn off the radio circuit when it is not needed. TDMA has a natural advantage over contention based medium access methods [5]. In TDMA, nodes listen and send data in a certain schedule. In other cases, node does not need to use radio circuit. So, it can turn off its radio circuit. One of the main problems of TDMA based networks is slot assignment. In this paper, a new distributed time slot assignment mechanism (DTSM) is proposed for TDMA based sensor networks. The most important design considerations of this new mechanism are energy efficiency, delay, and scalability.

Distributed time slot assignment is not a new topic for wireless networks. DTSAP (Dynamic Distributed Time Slot Assignment Protocol) [6- 8], FPRP (Five-Phase Reservation Protocol for Mobile Ad Hoc Networks) [9], E-TDMA (Evolutionary-TDMA Scheduling Protocol) [10], HRMA (Hop-Reservation Multiple Access) [11] are examples of distributed scheduling protocols for ad hoc networks. Most of the ad hoc network algorithms are developed for peer to peer data traffic. However, data traffic in WSN is mostly convergecast. Existing slot assignment algorithms for ad hoc networks can not satisfy energy and delay requirements of WSNs under convergecast traffic. Wireless sensor networks need a delay sensitive and energy efficient slot assignment algorithm under convergecast data traffic. This is why slot assignment algorithms developed for ad hoc networks can not be directly applied to WSN.

There are some researches about distributed time slot assignment for sensor networks. Patro et.al. has proposed Neighbor Based TDMA Slot Assignment Algorithm for WSN [12]. A mobile agent visits every node and assigns a proper slot. This method reduces required number of slots and increases channel utilization. However, it is not energy efficient. Copying and running the agent consumes high amount of energy. Kanzaki et. al. has also proposed an adaptive slot assignment protocol for WSN [13]. However, the main design objective is channel bandwidth, not delay or energy efficiency. Another distributed slot assignment algorithm for sensor networks is presented in [14]. It reduces delay for broadcast, convergecast, and local gossip traffic patterns for different grid topologies. However, in many sensor network applications, sensor nodes are deployed randomly. In addition to this difficulty, it does not consider energy consumption; its design consideration is only to minimize delay. SMACS [15] uses a different distributed time scheduling algorithm. After a series of handshaking signals,

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neighbor nodes can agree on a frequency and time pair to construct a link. SMACS produces a scalable and reliable flat network. However, SMACS needs FDMA as well as TDMA, but sensor nodes are so tiny and limited that current sensor nodes cannot meet the requirements of SMACS. DRAND [16] is a randomized dining philosophers algorithm for TDMA scheduling of wireless sensor networks. This algorithm is the first distributed implementation of RAND [17], a commonly used, centralized channel assignment algorithm. Randomized dining philosophers approach is scalable and robust. However, in DRAND, before having a schedule, nodes communicate with each other using a contention based MAC protocol, and it increases energy consumption. In [18], another distributed slot assignment algorithm is proposed. It also uses CSMA/CA to schedule the slots and it consumes high energy during slot assignment period, like DRAND [16]. μMAC has another slot assignment mechanism that includes a contention period [19]. TRAMA [20] is a TDMA-based sensor network system and it includes a distributed slot assignment mechanism. It has random access period to be able to assign proper slots, and its random access period is also contention based. In TRAMA, all the nodes have to listen to medium in random access periods. It increases energy consumption of TRAMA.

In this paper, a new delay sensitive, energy efficient distributed time slot assignment algorithm, DTSM, is proposed for wireless sensor networks. The design considerations of DTSM are delay, energy consumption, and scalability. There are a number of advantages of DTSM design over the existing designs. Firstly, unlike existing slot assignment protocols that includes 802.11 like contention sessions, nodes in DTSM contend in time slots, like FPRP [9]. In 802.11 like contention based sessions, all nodes must listen to medium and keep their radio circuits open during contention based session. This strategy may consume high amount of energy. Contention in time slots results in lower energy consumption. Another important feature of DTSM is its convergecast traffic aware design. Most of the time, wireless sensor networks use convergecast traffic pattern. In convergecast traffic, data relays from nodes into the sink. The sink collects all the data produced by the nodes. DTSM assumes that nodes always forward data to their neighbors that are with lower hop number. In order to decrease delay, DTSM assigns the slots on the basis of the hop number of the nodes. Unlike the other slot assignment algorithms, DTSM allows to assign the same slots into the nodes within two hop region, if the assignment allows convergecast traffic.

The rest of this paper is organized as follows. In Section II, details of existing time slot assignment algorithms for sensor networks are discussed. In Section III, system design of the proposed algorithm is introduced. In Section IV, performance results and discussion are presented. Finally, the conclusion is given in Section V.

## I. RELATED WORK

Instead of distributed algorithms, many TDMA based MAC protocols for sensor networks prefer to assign time slots centrally [21]. Especially, sensor networks based on small clusters prefer centralized approach as in [22-24]. Sensor nodes connect to the nearest cluster head. Cluster head collects data about the nodes in its cluster and creates a schedule centrally. Cluster head broadcasts this schedule to its nodes. However, this approach has disadvantages. Data about sensor nodes must be forwarded to cluster head with a contention based system like 802.11 [25] which increases energy consumption. Inter-cluster interference is another problem of these sensor networks. In most of the cases, interference is handled with CDMA approach which requires considerable computation power. Even if these disadvantages can be handled, all sensor networks are not cluster based and there is no easy way to implement central time slot assignment for wireless sensor networks that are not cluster based.

Most of the existing slot assignment algorithms for sensor networks are based on 802.11 like contention periods. SMACS [15], DRAND [16], TRAMA [20] can be classified in that kind of networks. They have a random access period. Slot requests and slot grant data exchanges are performed in this period. In this paper, TRAMA [20] is presented as an example. Time Slot organization of TRAMA is presented in Figure 1. It has two major components, scheduled access and random access. Scheduled access is basically used for data transmission. In this period, there is no contention. However, as the name suggests, during the random access period, nodes perform contention-based channel acquisition and thus signaling packets are prone to collisions. All the nodes have to listen to medium in random access period. Scheduled period is seven times longer than random access period. It must listen up to %12.5 of the time. Although it saves energy with respect to 802.11, it is still very serious energy waste when it is compared with a TDMA based system.

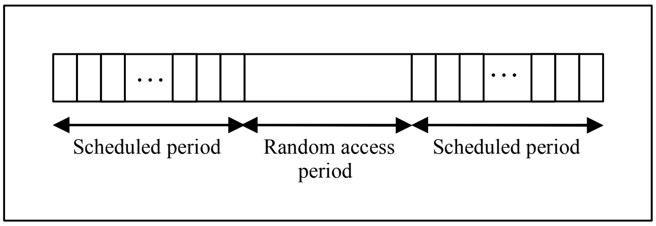


Fig. 1. Time slot organization of TRAMA

Another approach for distributed slot assignment is to use tiny time slots. In this approach, all nodes are assumed as synchronized. Nodes send their requests and grants in tiny slots. After a series of handshaking, if a node can receive the required signal successfully, it gets the slot. Five-Phase Reservation Protocol, FPRP [9], is one of the most known examples of this class of distributed slot assignments.

FPRP is a slot assignment protocol which uses five-phase reservation process to establish TDMA slot assignments that are non-conflicting with high probability [21]. It is fully distributed and can run parallel in the network. In other words, it is entirely insensitive to network size. Unlike TRAMA, it does not need the support of additional MAC protocol like 802.11 [25].

In FPRP, slots are assigned in a reservation frame which is a collection of reservation slots. The number of reservation slots is equal to the number of slots that will be assigned. Each reservation slot corresponds to a slot. Reservation slots are composed of a certain number of reservation cycles. The number of reservation cycles in each reservation slot is a fixed parameter of the algorithm. The nodes perform a special five phased handshaking procedure in a slot reservation cycle. All the phase handshaking are sent in slots, not in random access period. The first phase is reservation request. In this phase, the node that has no valid slot sends a request signal with a certain probability. The nodes that do not send a signal listen to the medium. In the second phase, collision report phase, nodes that receive a jammed signal in phase 1, send a collision report. In the reservation confirmation phase, a node that has sent a request in phase 1 and did not receive any signal in phase 2 allocates the current slot. In this case, it sends a confirmation signal in phase 3. In the reservation acknowledgment phase, a node that receives a signal in phase 3 sends a signal. At the end, in phase 5, a node that receives a signal in phase 4 sends a signal. A reservation cycle is composed of these phases. If a node can achieve to allocate a slot in a reservation cycle which belongs to $n^{th}$ reservation slot, it allocates $n^{th}$ slot.

## II. SYSTEM DESIGN

### A. Overview and Assumptions

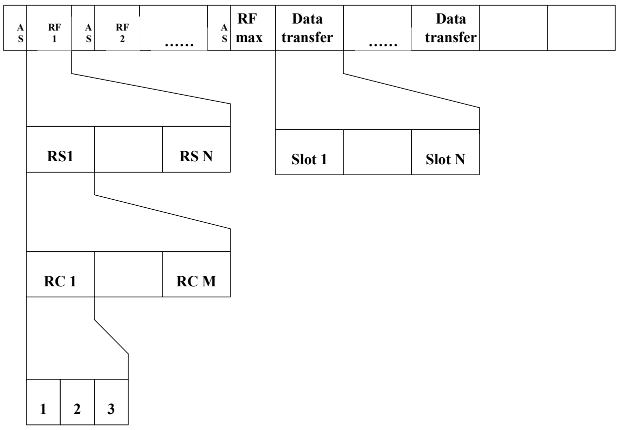
DTSM is a new distributed time slot assignment protocol for sensor networks under convergecast traffic. It is developed to operate with low energy, low delay. Because of its distributed nature, DTSM can be run in any network size without central node. It does not need any additional MAC layer support. It has a new mechanism to reduce delay, so it can be used in delay sensitive applications, like military monitoring. Before explaining the details of DTSM, assumptions are presented as follows:

- Sensor nodes will be immobile.
- Radio channel is symmetric.
- Before running DTSM, all nodes must synchronize their clock. There are many time synchronization schemas for sensor networks [18, 24].

### B. Description

Instead of using a random access period like TRAMA [20] or DRAND [16], DTSM uses time slots to exchange scheduling signals. The slot organization of DTSM is presented in Figure 2. The number of reservation frames, the number of reservation slots and the number of reservation cycles for each reservation slot are fixed parameters of DTSM.

DTSM assigns the slots in reservation frames. Every reservation frame begins with an advertisement slot. The nodes that receive the valid slot in the last reservation frame send a special signal in this slot. All the other nodes listen to this slot and if a node receives a signal in the slot it means the reservation frame for its hop number is about to begin and it can compete for slot assignment. Every reservation frame is used for corresponding hop numbered nodes. According to this hop numbered structure, in the first reservation frame, the nodes with hop number one can get slots. After that, the nodes with hop number two get the slots and so on.



AS: Advertisement Slot, RF: Reservation Frame, RS: Reservation Slot, RC: Reservation Cycle

Fig. 2. Slot organization of DTSM.

Slot assignments for a specific hop number are performed in reservation slots. Each reservation slot corresponds to a specific available data transmission slot. In this case, the number of reservation slots and the number of available data transmission slots for a particular hop number are the same. There are a certain number of reservation cycles in each reservation slot. The number of reservation cycles for each reservation slot is a constant and it is a parameter of DTSM algorithm. There are three tiny slots in each reservation cycle and signal exchanges are realized in these slots.

### C. Signal Exchange

In traditional slot assignment, no node within two hop radius can get the same slot. However, if the only traffic in the network is convergecast, this rule can be relaxed. If data flow through the higher hop numbered nodes to lower hop numbered nodes, convergecast traffic can be realized. DTSM assumes that a node with hop number $h$ sends its data only to a node with hop number $h-1$. In such a network, the only collision that must be handled is between the nodes with hop number $h$ and the nodes with hop number $h-1$. Even if they are in two hop neighborhood, the nodes that are with the same hop number can get the same slot, because they will never communicate. Figure 3 shows a sample slot assignment for a certain topology. In Figure 3, node A and B are with hop number $h$, node C and D are with hop number $h-1$. In this topology, C can hear A, but cannot hear B. D can hear B but cannot hear A. A and B can hear each other. In traditional slot assignment algorithms, A and B can not have the same slot. When A and B have the same slot number, they can not send data to each other. However, traffic is generally convergecast in WSN and if all data are forwarded from $h$ to $h-1$, convergecast traffic can be realized. The only requirement of a sensor network is to be able to send data to lower hop numbered nodes. In Figure 3, A must be able to send data to C and B must be able to send data to D. The only requirement is that A and C or B and D can not get the same slot. Although the same slot is assigned in two node neighbor nodes, network is still collision free for convergecast traffic.

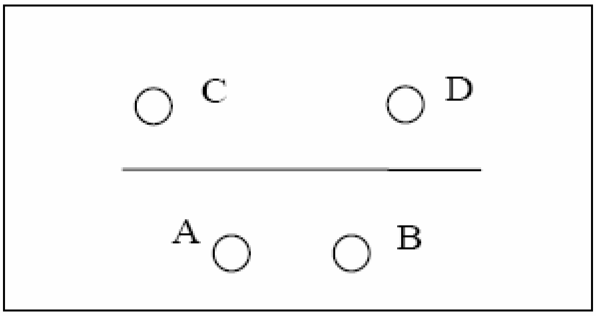


Fig. 3. Sample slot assignment.

According to this new situation, signal exchange is designed as follows: The first slot of a reservation cycle is request slot. In this slot, every node that receives a signal in the last advertisement slot requests a slot with a certain probability. Let us assume that the hop number of the node is *h*. For a valid request, it sends a signal in request slot. Only the nodes with hop number *h-1* may suffer from the collision of the requests. The nodes that are with hop number *h-1* listen to the request slot. If the node receives a jammed signal in this slot, it means there is a collision. The nodes that can get a valid request in the first slot send an approval signal in the second slot which is the approval slot. The nodes in the hop number *h* listen to the approval slot. If a node has sent a request and if it can receive a signal at the approval slot, it can get a valid slot. In the last slot which is the confirmation slot, the node that can get a valid slot sends a signal. The other nodes with hop number *h* listen to the confirmation slot. At the end of this signal exchange some nodes can get valid slots.

The diagram of all slot assignment signal exchanges is illustrated in Figure 4. In this scenario, A and B can hear each other. C can communicate only with A. Hop number of A and B is *h*. Hop number of C is *h-1*.

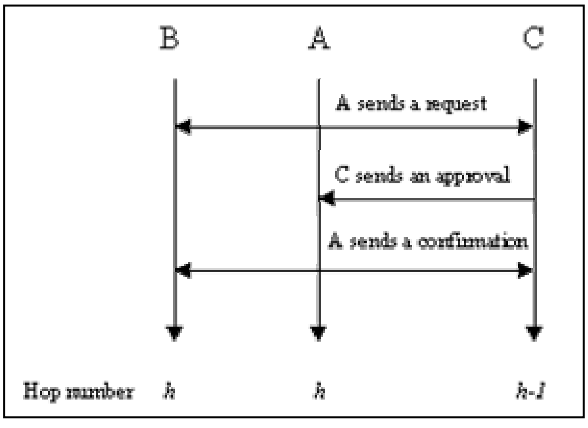


Fig. 4. A successful signal exchange scenario.

### D. Updating Slot Request Probability

At the beginning of the signal exchange, every node can send a request signal with a certain probability. This probability is not constant. It is calculated as 1/*Nc*, where *Nc* is the number of contender nodes in one hop neighborhood. *Nc* is updated at the end of each reservation cycle. *Nc* must be forecasted as realistic as possible. If *Nc* is forecasted larger than it is, contention probability will be l”ower than it should be and slot assignment algorithm may take longer than it is needed. If *Nc* is forecasted smaller than it is, contention probability becomes larger than it should be and collisions increases. *Nc* should be updated according to the result of reservation cycle. If a neighbor node can get a valid slot, number of contenders decreases. If there is a collision, *Nc* must be increased to decrease contention probability. If nothing happens, in other words, if the reservation cycle is idle, *Nc* should be decreased to increase contention probability.

DTSM slot request probability update strategy is similar to FPRP[9]. FPRP is also adopted from Rivest’s pseudo-Baynesian Broadcasting Algorithm [26], which is designed for distributed single hop ALOHA broadcast network. According to DTSM strategy, if a node can not receive or send any signal in a reservation cycle, it is idle. In idle state, *Nc* is decreased by one. If a node sends a request in the first slot and if it can not get approval in the second slot, it is a collision. For a collision situation, *Nc* is increased by $(e-2)^{-1}$. If a node sends a request and receives an approval in the second slot, it is a success for itself. It gets a valid slot and it does not contend anymore. If a node that does not send a request and receive a confirmation, it means there is a success one hop away. In addition to *Nc*, a new value must be calculated to update *Nc* for success state. This new value, *Nb*, represents the number of the nodes that has no valid slot and can not contend due to a success within one hop. The assumption is that if there is a success one hop away, a portion of its neighbors which is modeled as *R* can not contend. After a success one hop away, *Nb* must be increased by *R*Nc* and *Nc* must be recalculated as *(1-R)* Nc*. For the beginning of each reservation slot, *Nc* is set to a constant that is related with node density.The complete structure of updating slot request probability is as follows:

```
At the beginning of each reservation slot Nc= Nb, Nb =0.
For each reservation cycle
        Contention probability=1/ Nc.
        If the state is
          Idle:      Nc = Nc -1, if Nc >=1.
          Collision:   $Nc = Nc + (e-2)^{-1}$
          Success one hop away:
            (node does not contend in this reservation cycle)
            Nc = Nc -1, if Nc >=1.
            Nb = Nb + R* Nc.
            Nc = (1-R)* Nc.
```

### E. Handling Delay Problems

One of the most important design issues for wireless sensor networks is delay. If application is delay sensitive, like military monitoring or surveillance as in [27], data latency can be very important. In a military monitoring system, the existence of enemy should be reported as soon as possible. Reducing delay is possible by the help of assigning time slots carefully. The rule is that smaller hop numbered nodes should get higher slot numbers. In order to realize rescheduling, time frame is divided into $u$ sub time frames. If the whole time frame has $s$ slots, a sub time frame has $s/u$ slots. The slot number assigned to a node with hop number $h$, must be in $(u-((h-1) \bmod u))^{th}$ sub time frame. In this way, the slot numbers of consecutive hop numbered nodes belong to consecutive sub time frames. Sensor node can get the number of sub time frames, $u$, from the sink's synchronization signal and calculate its sub frame number.

Let us assume that the nodes in Figure 5 are one hop away from its consecutives. In this particular network, time frame has 30 time slots and there are 3 sub slots. In this case, the first sub slot is from 21 to 29th slots, the second is from 11 to 20th slots, and the third one is from 2 to 10th. The first slot is reserved for the sink. Figure 5 (a) is an example of a slot assignment. Figure 5 (b) is a slot assignment based on DTSM.

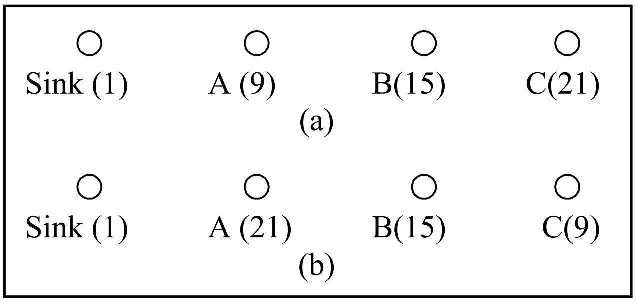


Fig. 5. Example network and time slots
(a) A regular slot assignment. (b) DTSM

The relay of an event from C to the sink takes 70 time slots for a sensor network in Figure 5(a). However, it takes only 21 time slots for the rescheduled network in Figure 5(b).

The pseudo code of DTSM is as follows:

```
n is the number of slots     // n and m are constants
m is the number of sub frames

MyHop=0
While  AdvSignal=0

// receives a  valid advertisement signal
 Receive(AdvSignal)
 MyHop=MyHop+1
Wend

// This part is for contention
CurrentSlot=0
While CurrentSlot<MaxSlot
// loop for reservation slots
 CurrentSlot= CurrentSlot+1
 For i= 1 to M[CurrentSlot]
// reservation slot contains M reservation cycle
   for ContentionProbability, send a request signal
   // request slot
   otherwise, listen to request slot

   Receive(ApprovalSignal)
   // approval slot
   If it receives an approval signal then
    Send (ConfirmationSignal)
    MySlot = CurrentSlot + (m-((h-1) mod m)-1)*(n/m)
    // Current slot in the current sub frame
  Else
    Receive (ConfirmationSignal)
  End if
   Update (ContentionProbability)

 Next i
Wend

// This part is for sending approval
Send (AdvSignal)
CurrentSlot=0
While CurrentSlot<MaxSlot // loop for reservation slots
 CurrentSlot= CurrentSlot+1
 For i= 1 to M[CurrentSlot]
// reservation slot contains M reservation cycle

   Receive (RequestSignal) // request slot

   If it receives a valid request signal then // approval slot
    Send (ApprovalSignal)
  End if

 Next i
Wend
```

## III. PERFORMANCE RESULTS

Performance of DTSM is discussed according to delay, energy consumption, and running time. A simulator is implemented to compare DTSM with FPRP, TRAMA and DRAND. Sensor network is assumed to be composed of Berkeley's Motes [28]. Berkeley's Mote has 19200 bit/s radio circuit. Power consumption of the radio transceiver, is 13.5mW, 24.75mW, in receiving and transmitting respectively [28]. So, receiving energy for one bit is 0.7 µJoule and transmitting energy for one bit is 1.29 µJoule. Simulation area is assumed to be a circle of 1000 m. diameter. The sink is placed at the center of the simulation area. The locations of the nodes are uniformly distributed over the simulation area. Simulator parameters are presented in Table 1.

TABLE 1. SIMULATION PARAMETERS

| PARAMETER | |
|---|---|
| Shape of the sensor network area | Circle |
| Diameter of sensor network | 40 unit |
| Transmission Range | 1.5 unit |
| Sensing Range | 1 unit |
| Bit rate | 19200 bit/sec |
| Receive energy (one bit) | 0.7 µJoule |
| Transmit energy (one bit) | 1.29 µJoule |
| Number of bits in one signal exchange time slot (including synchronization bits) | 5 bits |
| Time for one data transfer time frame | 1 sec. |
| Number of sub frames (DTSM), u | 5, 10, 20, 30 |
| Contention Probability Parameter for DTSM (R) | 0.8 |

Another parameter for simulation is the number of reservation frames for DTSM and the number of reservation cycles in each reservation frame. Number of reservation frames and reservation cycles should be set so that slot assignment algorithm can assign valid slots with high probability and it should minimize energy consumption and run time. In order to find optimum parameters, a central coordinator is developed for FPRP and DTSM. The pseudo code of central coordinator is as follows:

```
While (there is at least one node that is connected to the
network and can not get a valid slot) do
  If there is at least one node that can get the current
      do_DTSM or do_FPRP
  else
      increase reservation cycle and current slot number by 1
  end if
Wend
```

If a node can get the current slot, reservation cycles are continued to repeat and if there is a node that can not get a valid slot in the current slot, reservation frames are continued to repeat. In this way, minimum number of slots is assigned to the nodes. Average number of reservation cycles and reservation frames are calculated after 20 runs with central coordinator and the calculated numbers are used as parameters. The most important factor that affects these parameters is the node density. Number of reservation cycles and reservation frames is set for each node density. Simulation results have shown that the parameters that are calculated with this methodology can assign valid slots with more than %99.5 probability. Number of reservation cycles in each reservation frame is presented in Figure 6 for FPRP and DTSM, when the node density is 1.

Fig. 6. Number of reservation cycles for each reservation frame for DTSM and FPRP, when node density is 1.

### A. Delay

Delay is one of the most important problems for sensor networks. Especially, delay sensitive applications like military monitoring, may suffer latency. DTSM has a special mechanism for handling the delay problem. Delay performance of DTSM is compared with FPRP. Any other slot assignment mechanism that has no delay handling mechanism is expected to result like FPRP.

In the simulation, one data transfer time frame is assumed as one second. If a packet is composed of 64 bits, and a node can send one packet in one data slot, one data slot takes 3.3 ms. One sub time frame for DTSM is composed of 9 slots, if the node density is 1. In our simulation, sub time frames are 5, 10, 20 and 30. Delay is related to the distance between event and the sink. In order to investigate the delay performance, circular network area with 40 unit diameter is divided into 10 regions. The first region is 2 unit distant from the sink. The second is 4 unit distant from the sink, and so on. 100 events are generated for each region and simulation is repeated for 20 times. Figure 7 shows average delay of DTSM and FPRP.

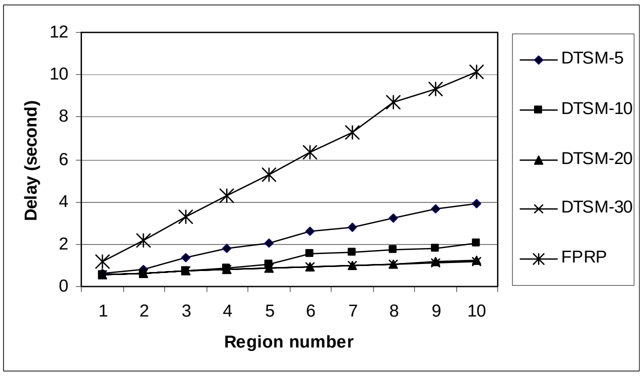


Fig. 7. Delay performance of DTSM and FPRP.

FPRP delay increases with the distance linearly. If distance between event and the sink is 40 unit, in other words in region 10th region, FPRP delay exceeds 10 seconds. If it is assumed that 1 unit is 30 m., FPRP can report a 600 m. away event within 10 seconds. If the application is delay sensitive, for example military monitoring or intruder detection system, this delay is unacceptable.

DTSM is successful to decrease the delay with its sub frame structure. Especially, when the distance is long and sub frame number is high, delay difference between DTSM and FPRP may increase up to 9 times. DTSM with 20 sub time frame can report an 600 m. away intruder in only 1,1 second. Delay performance of DTSM is acceptable for most of the delay sensitive applications.

Although sub frame number affects delay performance, it is not always directly proportional to the sub frame number. The delay performance of DTSM follows a step pattern related to the average hop number between event and the sink. For example, average hop number for 5th region is 10, and delay of DTSM-20 and DTSM-10 is approximately the same. After the 5th region, while delay of DTSM-10 increases, delay of DTSM-20 still stays almost constant. The same structure can be found for DTSM-5. This step pattern is closely related to the average hop number of the region and the number of sub frames. Average hop number of the 5th region is 10 and delay values of DTSM-10, DTSM-20, DTSM-30 are very close for region 5. If region number is higher than five, average hop number exceeds 10 and delay of DTSM-10 starts to increase.

While delay of DTSM-10 increases, DTSM-20, DTSM-30 stays approximately constant. It shows that sub frame number must be chosen according to average hop number of the sensor network. If sub time frame number is lower than maximum hop number, delay increases.

### B. Energy Consumption

Sensor nodes have limited energy and when the power goes off, sensor node can not function. Energy is one of the most critical resources for sensor networks. Slot assignment mechanism of a sensor network must be energy saver like any other algorithm used in sensor networks.

It takes considerable energy. DRAND uses 802.11 like signal exchange mechanism and it needs very large amount of signaling. FPRP does not use any additional MAC layer for slot assignment. However, it is not optimized for energy consumption. DTSM is a distributed slot assignment algorithm designed for minimum energy consumption.

One of the most important parameters for energy consumption for DTSM is node density. The simulation results for different node densities are presented in Figure 8 to compare energy consumption of DTSM, FPRP, DRAND and TRAMA. In Figure 8, energy consumption of neighbor discovery and tree construction algorithms of TRAMA is not included. Energy consumption of the algorithms increases with the increasing node density. While increasing structure of DTSM and DRAND is polynomial, energy consumption of FPRP and TRAMA increases linearly. It is clear that time slot assignment protocols that include contention period, like TRAMA or DRAND consume much more energy than slot assignment protocols based on tiny time slots, like FPRP or DTSM. Although FPRP is also successful when it is compared with contention period based methods, DTSM performs approximately 4 times better than FPRP.

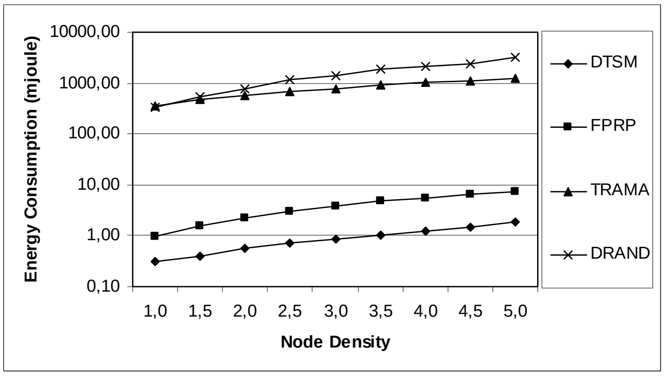


Fig. 8. Energy consumption comparison of different time slot assignment algorithms.

### C. Minimum Number of Distributed Slot

Number of distributed slots is another important performance issue for slot assignment algorithms. Slot assignment algorithm should assign minimum number of slots to maximize the bandwidth for each node. In order to find the minimum number of distributed slots, a central coordinator is assumed. Central coordinator tries to detect the nodes that can have the current slot. If there is such a node, reservation cycles are continued to repeat. If there is no node that can get the current slot, and there is a node that can not get a valid slot, the next reservation frame is created.

To color a graph with minimal number of colors is NP-complete and is often intractable for a network of reasonable size [29]. The performance of FPRP and DTSM is compared to a degree lower bound (DLB). This degree lower bound is the maximal degree of the graph plus one. Minimum number of slots distributed with FPRP, DTSM and DLB for different node densities is compared in Figure 9.

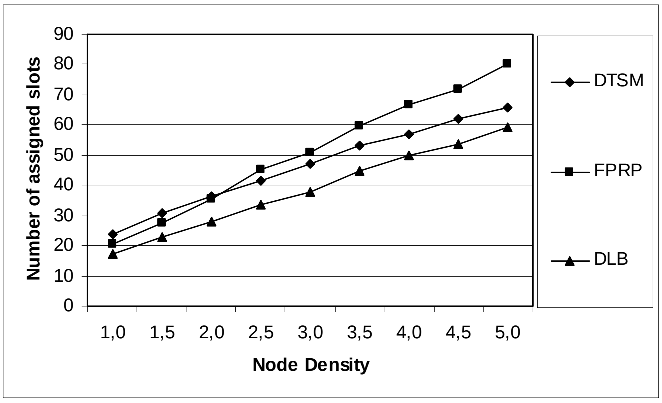


Fig. 9. Minimum number of distributed slots and degree lower bound for different node densities.

When node density increases linearly, FPRP, DTSM and DLB increases also linearly. FPRP can perform better than DTSM for lower node densities. However, if the node density is higher than 2, DTSM becomes better than FPRP. Neither FPRP nor DTSM can perform better than DLB. However, when the node density is higher than 2, DLB and DTSM are very close.

### D. Running time

DTSM and FPRP are compared regarding their running times. FPRP is a fully parallel and distributed algorithm. All the nodes can run the FPRP algorithm at the same time. The reservation process for a given node only involves nodes within a two-hop radius, and is thus a local process. No coordination is necessary with more distant nodes. By keeping the reservation process localized (and running simultaneously over the entire network), the FPRP is insensitive to the network size. Its running time is constant. However, nodes run DTSM according to their hop numbers. It follows a wave pattern from the lowest hop number to maximum hop number. In the first reservation frame, the nodes which are one hop away from the sink allocate a certain set of slots. In the second reservation frame, the nodes which are two hops away from the sink allocate the slots and so on. In this case, running time of DTSM is fully dependent on the maximum hop number of the network.

Running time of FPRP is as follows:
$R_{FPRP}$= 5* time for one signal exchange slot * total number of reservation cycles in reservation frame.

Running time of DTSM for one hop is as follows:
$R_{DTSM}$= 3* time for one signal exchange slot * total number of reservation cycles in a reservation frame * maximum hop number + time for advertisement signal*maximum hop number.

Simulation model is used to compare running times. In Figure 10, average running time of DTSM with different maximum hop numbers and FPRP are compared for different network sizes, if it is assumed that every signal exchange slot has 5 bits and there are two guard bits between each signal exchange slots. Average running times are calculated with considering 20 simulation runs.

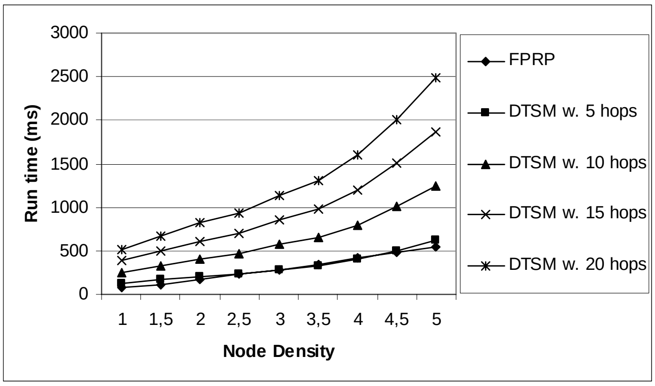


Fig. 10. Running time of DTSM and FPRP for different network size.

FPRP run time does not change with network size. Running time of DTSM is dependent on the size of the network and it is proportional to the maximum hop number of the sensor network. When the node density is 5 and the maximum hop number is 20, DTSM run time is 2,5 seconds. Simulation results have shown that the diameter of such a network can be 50 units. For a sensor network with 50 unit diameter, DTSM takes 2,5 seconds. For a typical sensor network, if 1 unit is assumed as 30 m, DTSM can assign time slots in a sensor network with 1500m diameter in 2,5 seconds. For the same network size, FPRP can assign time slots in slightly more than 500 ms. Although FPRP can run much faster than DTSM, DTSM is also acceptable even for time critical applications.

While FPRP and DTSM can run in the order of seconds, simulation implemented in [16] has shown that DRAND takes approximately 25 seconds when node density is 1. DRAND run time fits a quadratic curve with varying node densities. When node density is 5, DRAND takes approximately 240 seconds which is much longer than run time of FPRP and DTSM.

## IV. CONCLUSION

In this paper, a new delay sensitive and energy efficient distributed time slot assignment algorithm for wireless sensor networks (DTSM) is proposed. It assumes that data traffic of sensor network is convergecast and data always flow from higher hop numbered nodes to lower hop numbered nodes. Although hidden node problem does not allow assigning the same node within two hop neighbors, DTSM can assign the same slot within two hop neighbors by the help of convergecast traffic assumption. In order to compare DTSM and well-known distributed slot assignment algorithms, a simulator is developed. Extensive set of simulation results show that delay and energy consumption performance of DTSM is superior to that of FPRP [10], DRAND [16] and TRAMA [20]. Another metric for DSTM is the number of distributed slots. While traditional slot assignment algorithms do not allow assigning the same slot within two hop neighbors, because of the hidden node problem, DTSM can assign, if assignment is suitable for convergecast traffic. This DTSM characteristic concludes that it can distribute less number of slots than traditional distributed slot assignment algorithms, like FPRP. Although DTSM can realize low energy consumption, delay and number of distributed slots, its running time proportionally increases with sensor network area. Fortunately, DTSM can run under in acceptable run time even for a large wireless sensor network such as a network with 1500 m diameter.

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