TSCH Slotframe Optimization Using Differential Evolution Algorithm for Heterogeneous Sensor Networks

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Abstract: The Time-Slotted Channel Hopping (TSCH) from the IEEE 802.15.4 standard aims at providing high reliability to industrial wireless networks. One of the most significant challenges in TSCH is determining the schedule. In this paper, we present an algorithm to find an optimal TSCH schedule with the minimum slotframe size that can meet the desired throughput of each node. A customized Differential Evolution (DE) optimization algorithm was developed based on the determination of an interference and collision free transmission graph which has not been used in prior works. Our schedule can encompass sensors with different packet rates and results in a low transmission delay of the data packets. Using Matlab, we performed various complexity analysis to measure the time it takes to find the optimal schedule in different scenarios. Additionally, we implemented the optimal TSCH schedule on TSCH-SIM simulator to confirm that the schedule is working promising. As a result, the high value of the Packet Delivery Rate (PDR) obtained from the simulations verified the schedule performance.

1 INTRODUCTION

TSCH is a synchronous MAC (Medium Access Control) protocol, specified in the IEEE 802.15.4 standard amendment (Watteyne et al., 2016). To provide more reliability to upper network layers, TSCH (IEEE Std 802.15.4-2011, 2011) (Howitt and Gutierrez, 2003) combines Time Division Multiple Access (TDMA) and Frequency Division Multiple Access mechanisms (FDMA). Former allows several users to share the same frequency channel by dividing the signal into different time slots, while latter allows multiple users to send data through a single channel by dividing the channels' bandwidth into separate non-overlapping sub-channels and allocating each sub-channel to a separate user. In other words, TDMA separates users by time and FDMA separates users by frequency.

In TSCH, medium access is orchestrated by a schedule that is distributed to all the nodes in the network. The network coordinator is responsible for management and control of traffic flows and also it computes the optimized time slot and channel assignment (Urke et al., 2021). (Teles Hermeto et al., 2017). For each pair of nodes, a cell in the schedule is allocated to specify when and in which channel the transmissions will take place. A cell is indicated by a tuple as (timeslotOffset, channelOffset) and it can be shared by multiple transmissions or dedicated to only one transmission. The standard does not define how TSCH packet transmission schedule is defined (Urke et al., 2021).

Industrial sensor networks are expected to accommodate sensors with different packet rates, and this makes it particularly challenging to determine an optimal transmission schedule for the network. For instance, consider two sensors generating 4 and 100 packets/sec, respectively. Determining an optimal slotframe length for the flows is important, since a short slotframe length results in too many repetitions of a slotframe prior to the data generation, whereas a schedule with a long slotframe will suffer high end-to-end delays. Consequently, the slotframe should be long enough to include all the required transmissions by considering the estimated number of generated packets.

In this paper, we propose a novel slotframe length optimization for TSCH scheduling based on the Differential Evolution (DE) algorithm to minimize the overall network delay while maintaining the expected packet transmissions in the network. Delay optimization problem is identified as a combinatorial optimization problem and is known to be NP-hard (Ojo and

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Giordano, 2016) (Abu-Khzam et al., 2015). In this paper we leveraged the DE optimization algorithm to determine a sub-optimal schedule in terms of delay for a centralized managed heterogeneous sensor network. DE is a random search algorithm based on population evolution, proposed by Storn and Price (Storn and Price, 1997). This method performs optimization by iteratively trying to improve a candidate solution regarding a given measure of quality. It has been proven that DE is a reliable optimization strategy for many different tasks. In our problem the DE optimizer has to generate a number of schedules that are evaluated using an objective function to determine the best schedule.

This paper is structured as follows. Section 2 is a review of related works. Section 3 focuses on the proposed slotframe optimization using the customized DE optimization algorithm for TSCH and highlights the details of each step. The optimized schedule for a specific network topology is described in section 4 and the simulation results extracted from TSCH-SIM simulator are presented in section 5. Then, a time complexity analysis of the algorithm is performed in section 6. Finally, section 7 concludes this paper.

2 RELATED WORK

A conflict-free scheduling algorithm was proposed in (Soua et al., 2016), which targets the minimization of transmission delay by reducing the slotframe length. The author introduced the concept of ”WAVES”; which is a period where each node performs at least one packet transmission during the WAVE time. As a result, the slotframe length will be equal to the time when all the packets of each node are sent. In this paper, the nodes closer to the sink suffer high traffic overflows or queue overflow, and some nodes will suffer high delays in large networks. The packet rate of nodes is assumed to be homogeneous, although the total number of packets received from child nodes is different from others.

A debt-based scheduler is presented in (Minet et al., 2018). In this approach, a debt value is calculated for each TSCH device which has a message to transmit, that is equal to the multiplication of the remaining number of data messages the node has to transmit and the depth of device in the network. No spatial reuse was applied on cells in this paper, that is, a cell is granted to only one transmitter which results in including lower number of transmissions in a single time slot and higher delays accordingly. Similarly, Ines Khoufi et al. (Khoufi et al., 2017) proposed a multi slotframe to determine the lower bound number of slots required to perform data gathering and to support sensor flows with data delivery constraints. These two approaches (Khoufi et al., 2017) (Minet et al., 2018) only allocate one cell per node to handle all traffic. Therefore, the performance of the algorithm degrades under high traffic loads.

A centralized Adaptive Multi-hop Scheduling (AMUS) algorithm has been proposed in (Jin et al., 2016) to provide optimized schedules using tentative cell allocations. AMUS reserves additional cells for those links which might be heavily loaded, or prone to interference to improve communication reliability and achieve low latency. A Combinatorial Multi-Armed Bandit (CMAB) was proposed in (Javan et al., 2019) which determines the optimal scheduling by assignment of TSCH cells to links using the Linear Learning Rewards (LLR) algorithm. This is done using a bipartite graph that matches non-interfering links to slot-frame matrix cells. We also use a graph to represent non-interfering links but optimize this using a DE algorithm.

The Traffic Aware Scheduling Algorithm (TASA) (Palattella et al., 2012) aims at finding the minimal number of slots needed to send all data to a root node. To reach this goal, matching and coloring functions are used to plan the distribution of slots and channels across the entire network without any collision. First, links that still have data to transmit are selected at the corresponding time slot through a matching process. Then, the channel offsets of the links are allocated so that interference does not occur through the matching process.

The effect of different slotframe length on energy consumption is investigated in (Kharb and Singhrova, 2018), however, the goal of this paper is to find the minimum slotframe length that results in minimum energy consumption. Hill Climbing technique as a local search based mathematical optimization was used to discover the optimized slotframe length and the penalty function is used to provide a hill to climb when the optimization starts at undesirable location. The simulation results show that slotframe length and energy consumption have inverse correlation relationship.

Fafoutis et al. (Fafoutis et al., 2018) proposed an adaptive static scheduling that allows each pair of nodes to control their active time slots in a distributed manner in order to improve the energy efficiency of a TSCH network. A static scheduler was built at compilation time with excessive time slots over allocation yet, the nodes can dynamically activate or deactivate their a priori allocated time slots, according to the traffic requirements. However, the authors did not consider the cost of blind over-provisioning in terms

Table 1: List of notations used in this paper.

Symbol	Description
S_i	Sensor with ID i
V	Set of vectors includes all the collision and interference free transmissions as a pair of transmit-receive tuple
m	Size of space vector V
M	Matrix that keeps track of the interference and collision between transmissions
$M_{i,j}$	Transmission status of i and j'th pairs in V
L_{sf}	Slotframe length
N_{ts}	Number of timeslots in the slotframe
$PR(S_i)$	Packet rate of sensor S_i
$EP(S_i)$	Expected generated packets for sensor node S_i

of delay performance.

3 METHODOLOGY

To explain the algorithm, we use a simple tree topology as shown in Figure 1, consisting of a root node labeled as S_1 and three other sensor nodes as $\{S_2, S_3, S_4\}$. In this figure the green boxes show the number of packets each node generates in one second.

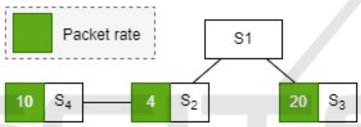


Figure 1: A simple tree topology consisting of 3 sensor and a root node.

In our context, the TSCH schedule is built with the concept of spatial reuse that allows each cell to be shared by multiple transmissions. Multiple transmissions allocation to a single cell will diminish delay due to the capability of encompassing higher number of transmissions in each time slot; however, it can also lead more potential collisions and interference while exchanging data. To address this concern, we have defined a *FreeSet* graph that captures transmissions among pairs of nodes that are collision and interference free. The transmissions in one set of the *FreeSet* can be assigned to a cell in TSCH schedule without causing any collision or interference.

Then, the expected number of transmissions is estimated for each sensor node according to its packet rate as well as its children's packet rate since each node is also responsible to relay the received packets from its children. Using a customized DE optimization algorithm, we found the minimum slotframe size that includes all the required estimated transmissions. Figure 2 is a flowchart describing the overall optimization procedure. In the following sections, each step of the algorithm is explained in more detail. The list of symbols and notations used in this paper is presented in table 1.

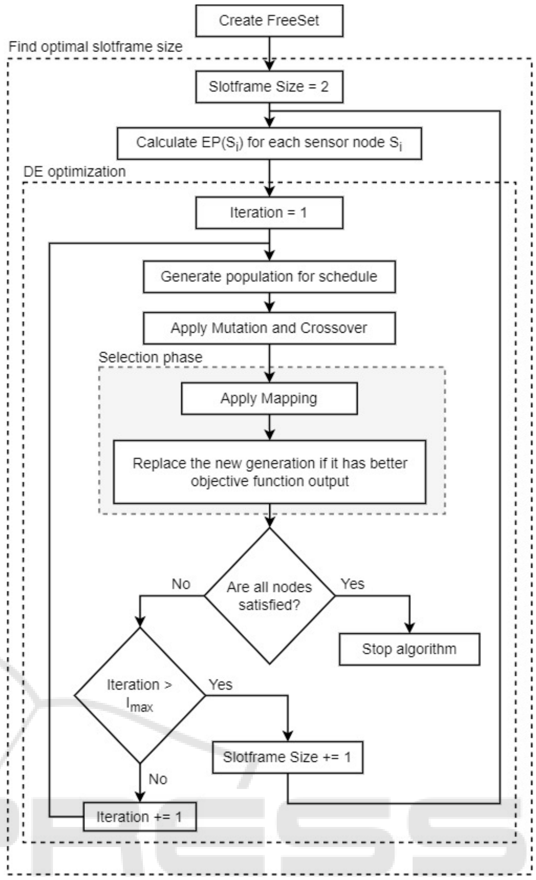


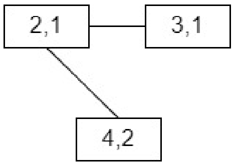
Figure 2: Flowchart for customized DE slotframe size optimization.

3.1 Creating the FreeSet Graph

Before applying the customized DE optimization, *FreeSet* is created, which consists of several set of node pairs that can be assigned to a single cell without causing any collision or interference. Assuming that A includes a set of transmissions as $\{A_1, ..., A_i\}$, A_i consists of the transmission / receive pair as $S_j \rightarrow S_k$, where j and k correspond to the node index values. In this case:

- A new transmission can be assigned to the same cell which is appointed to A only if it does not have any collision or interference with any of the transmissions in set A.
- The new transmission can be assigned to the same time slot which A has been assigned to, providing that it does not cause any collision with any of transmissions in A.

The union of collision and interference graph for the sample topology is depicted in Figure 3a. In this graph, the transmissions connected through an edge cannot be assigned to an identical cell as it will cause collision or interference. For instance, transmissions $S_2 \rightarrow S_1$ and $S_4 \rightarrow S_2$ are not allowed to be assigned to a single cell or time slot, since node S_2 cannot send and receive at the same time. As shown in Figure 3b, *FreeSet* is obtained from the complement of the graph 3a.



(a) .

Index	FreeSet
1	{(2,1)}
2	{(3,1), (4,2)}

(b) .

Figure 3: Union of the collision and interference graph (a) FreeSet (b).

As shown in Algorithm 1, we implemented the *FreeSet* graph as a vector space V that includes all the collision and interference free transmissions as a pair of transmit-receive tuple. Based on the example in Figure 1, this set would include the 3 transmissions as $V = \{ S_4 \rightarrow S_2, S_2 \rightarrow S_1, S_3 \rightarrow S_1 \}$.

We use a matrix as M to keep track of the interference and collision between transmissions, where $M_{i,j}$ represent the status of transmission pairs i and j in V. The values in the matrix can be 0, 1, or 2. A value of 0 implies that transmission i and j can be assigned to the same cell; a value of 1 implies that there will be interference if these two pairs transmit packets simultaneously but they can transmit their packets in different channels to avoid interference; a value of 2 implies that if the pair i and j transmit a packet at the same time collision will occur. Based on these values, collision and interference can be distinguished.

Below is an algorithm that creates the *FreeSet* from the vector V. The complexity of this algorithm is $O(m \cdot log(m-1))$ where m denotes the size of set V.

Algorithm 1: Creating FreeSet.

Input $V = \{V_1, V_2, ..., V_m\}$
Output *FreeSet*

$M_{c*c} \in \Re^2 : c = 1...m,\ m = |V|$
for $i = 1 : m$ **do**
  $Pair_1 \leftarrow V_i$
  for $j = i+1 : m$ **do**
    $Pair_2 \leftarrow V_j$
    Check the conditions for Collision and Interference for $Pair_1$ and $Pair_2$
    if ($Pair_1$, $Pair_2$) in collision **then**
      $M_{i,j} \leftarrow 2$
    else if ($Pair_1$, $Pair_2$) in interference **then**
      $M_{i,j} \leftarrow 1$
    else
      $M_{i,j} \leftarrow 0$
    end if
  end for
end for
FreeSet $\leftarrow$ Pairs in M with value 1
return *FreeSet*

3.2 Estimate the Expected Number of Packets Generated

A TSCH slotframe consists of several time slots and slotframe length can be calculated by multiplying the number of time slots in a slotframe by the time slot length. The slotframe should be large enough to transmit all the estimated number of packets within the slotframe time period. Nodes are synchronized and follow a schedule using a slotframe that continuously repeats over time.

For any particular slotframe, we estimate the number of packets that are to be transmitted in the network by computing the number of packets generated in that specific slotframe size and propagating this throughout the network topology. As example the simple 3 node topology shown in Figure /reffig:4-nodes is considered. The generated packet rate of these three nodes $\{S_2, S_3, S_4\}$ is {4, 20, 10} packets/sec, respectively. For the scheduler, we assume that all the data packets have been generated simultaneously after the network initialization phase. The highest delay that can exist is the case where a node generates a data packet and has to wait for the next slotframe to transmit. To avoid high delays, we estimate the number of cells each node needs according to its packet rate and their children's packet rate.

Considering a slotframe length as L_{sf} consisting of N_{ts} time slots, one can estimate the generated packets during the slotframe for each node S_i as $EP(S_i)$ using Equation 1. The result obtained from $L_{sf} \cdot PR(S_i)$ may be a fraction, although we need an integer value as the output for the expected number of generated packets. The most conservative approach to deal with fractions is to round up, which results in over scheduling of transmissions. Any other approach can originate the possibility missing a required transmission which cause an eventual queue overflow. After the number of packets generated during a particular slotframe size is calculated, the number of packets generated by the children are summed up as can be seen in Equation 1.

$$EP(S_i) = \lceil L_{sf} \cdot PR(S_i) \rceil + \sum_{j=1}^{M} EP(S_i.child(j)) \quad (1)$$

where $PR(S_i)$ denotes the packet rate of sensor node

S_i and $S_i.child(j)$ represents the j^{th} child of node S_i. Slotframe length L_{sf} is calculated through the following equation:

$$L_{sf} = L_{ts} \cdot N_{ts} \quad (2)$$

where L_{ts} is time slot length that is assumed as standard value of 10 ms and N_{ts} denotes the number of time slots in a slotframe.

3.3 Customization of the DE Optimization Algorithm

Using different channel offsets in TSCH schedule provides the opportunity for the interfering transmissions to be concurrently done without interference. Consequently, although we cannot schedule transmissions that collide with each other in the same time slot, we can schedule interfering transmissions in same time slot but on different channel offsets.

In initialization step of the DE optimization algorithm, the minimum population size is used to reduce the complexity of the computations. Minimally, 4 random solutions are generated in the search space of the DE optimization problem. Search space in our problem is set of transmissions in *FreeSet*; each can be of a different size which is not possible condition in Differential Evolution optimization process and was explained in details in (Vatankhah and Liscano, 2022).

In the Mapping phase, each value in the generated matrix is mapped to a transmission set in the *FreeSet* which is described thoroughly in (Vatankhah and Liscano, 2022). A node is labeled as *SATISFIED* or *NOT SATISFIED* which declares whether the sufficient number of cells have been assigned to the sensor node S_i based on the calculated $EP(S_i)$ value or not.

Moreover, while generating a schedule in the Mapping phase, we utilized a prioritization for choosing between two transmissions that collide in same time slot but different channels. While checking each time slot for possible collisions, we may discover transmissions causing a collision such as (S_i, S_r) and (S_k, S_r) due to the identical destination node. Transmission (S_k, S_r) will be chosen over the other transmission only if one of the circumstances listed below is met:

- S_i is labeled as *SATISFIED*
- $EP(S_k) >= EP(S_i)$

Providing that either conditions are met, (S_i, S_r) will be removed from the schedule. Afterwards, the schedule passes through the Mutation and Crossover phases of the DE algorithm. The details of Mutation and Crossover have been thoroughly explained in (Vatankhah and Liscano, 2022).

In the Selection phase, the generated schedule is compared to the existing one that was generated in initialization phase as shown in Equation 3. In this stage, the schedule with the higher objective function value will survive and will be replaced with the corresponding schedule. The objective is to maximize the Equation 3.

$$f(x) = Num(\sum_{i=1}^{N} S_i \,|S_i.lbl == SATISFIED) \quad (3)$$

where $S_i.lbl$ is equal to *SATISFIED* only if the number of cells that are assigned to sensor S_i is more or equal to the $EP(S_i)$. This function calculates the number of nodes that are labeled as *SATISFIED*. The algorithm will continue running on a specific slotframe length until all the sensor nodes labeled as *SATISFIED* or the iteration exceeds an iteration maximum value which has been set to 20 in the examples presented in this paper. If this maximum value is reached the optimization process will resume using a new slotframe size which is larger than the original one by one slot.

As depicted in Figure 2, block titled "DE optimization" shows when all the nodes are *SATISFIED*, the optimization is terminated, otherwise, slotframe size will increase by one and DE optimization will try to find a schedule that can satisfy all the nodes.

4 AN OPTIMIZED SCHEDULE SCENARIO

To evaluate the performance of the algorithm on heterogeneous traffic flows, a tree topology consisting of 14 nodes with the given packet rates was examined as shown in Figure 4, where the green boxes denote the packet rate of each node.

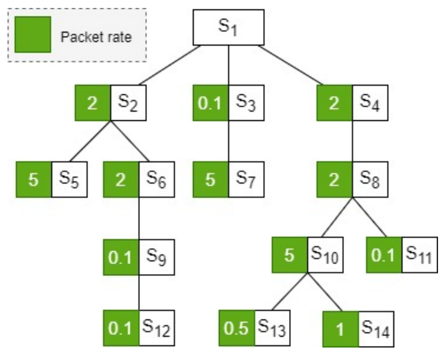


Figure 4: A sample tree topology of 14 sensor nodes.

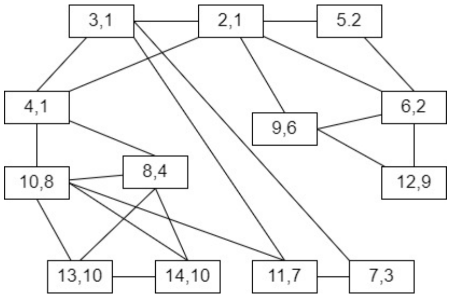


Figure 5: Union of collision and interference graph for the network depicted in Figure 4.

According to the given topology, the possible transmissions are $\{(S_2,S_1)$, (S_3,S_1), (S_4,S_1), (S_5,S_2), (S_6,S_2), (S_7,S_3), (S_8,S_4), (S_9,S_6), (S_{10},S_8), (S_{11},S_8), (S_{12},S_9), (S_{13},S_{10}), $(S_{14},S_{10})\}$ which are shown as graph vertices in Figure 5. Based on the collision and interference rules explained in section 3.1, the collision and interference graph was established as Figure 5.

For each slotframe size, the proposed algorithm calculates the number of expected packets for each node. Then, the Customized DE algorithm explores to find a solution that can accommodate all the expected number of transmissions. The expected number of generated packets for each node is calculated using Equation 1.

In this example, any fractional values are rounded up to the nearest integer. In this table, the number of generated packets and the number of the assigned cells for sensor nodes $\{S_2, S_3, ..., S_{14}\}$ are shown in the *EP* and *ASSIGNED* rows, respectively. From Table 2, it can be observed that the number of assigned cells in the optimized schedule is more or equal to the expected packet transmission values for each sensor node. The higher number of assigned transmissions for some nodes in the schedule is due to the fact that some of the *NOT SATISFIED* transmissions are co-located with *SATISFIED* transmissions in the same set of *FreeSet*. When the schedule tries to add the *NOT SATISFIED* transmission to the schedule, it also adds the already *SATISFIED* transmission.

Table 2: Expected number of packet generation for slotframe of size 15.

$L_{sf}=15$	**ID**	S_2	S_3	S_4	S_5	S_6	S_7	S_8
	EP	5	2	6	1	3	1	5
	ASSIGNED	6	3	6	4	5	12	6
	ID	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	
	EP	2	3	1	1	1	1	
	ASSIGNED	3	3	4	10	8	1	

For the given example in Figure 4, the algorithm terminates at a slotframe size of 15, when all the nodes are labeled as *SATISFIED* and Table 2 shows the expected and assigned transmissions for each of the slots. One can observe that the number of assigned slots is higher or equal to the expected.

After these assignments the TSCH schedule includes all the required number of transmissions to transmit the generated packets or relay the received packets from their children as illustrated in Table 3. In this table, multiple transmissions are scheduled to send their packets in the specified time slot and channel offset. For instance, sensor nodes S_2, S_7 and S_{12} are scheduled to transmit or relay the packets to nodes S_1, S_3 and S_9, respectively, in time slot 2 and channel offset 3.

Table 3: Schedule for the optimal slotframe size of 15.

	ts 1	**ts 2**	**ts 3**	**ts 4**	**ts 5**	**ts 6**	**ts 7**	**ts 8**
ch 1	11			6	11,13			
ch 2	13	2,7,12						
ch 3			8	3	9			
ch 4			2	8		12	2,7,12	
ch 5	2,7,12	8	7, 9, 13	12,13	2,7	6,3,8	8	10,2,7,12
	ts 9	**ts 10**	**ts 11**	**ts 12**	**ts 13**	**ts 14**	**ts 15**	
ch 1					4			
ch 2		4,7,13				4,5		
ch 3	6,3,8		4,5	4,5	11,7,12,13	11,13	4,13	
ch 4	14	5,9		10			6	
ch 5	12		10,7,12	7,12	6	7,12	7,12	

As explained earlier, the customized DE optimization initialized by setting slotframe length L_{sf} to 3. For the given topology, the number of *SATISFIED* nodes is 6 out of 14 nodes as presented in Table 4. The slotframe length increases by one in this case until all the nodes are *SATISFIED*. As it can be observed from Table 4, the schedule with slotframe length of 15 is found while all the 14 nodes are satisfied.

Table 4: Maximum number of SATISFIED nodes for each slotframe length.

L_{sf}	3	4	5	6	7	8	9
#SAT	6	9	9	10	10	11	12
L_{sf}	10	11	12	13	14	**15**	
#SAT	13	13	13	13	13	**14**	

5 SIMULATION

To evaluate the performance of the schedule obtained from our Customized DE optimization algorithm, we implement the optimized schedule in the TSCH-Sim (Elsts, 2020) network simulator for the scenario shown in Figure 4. The overall throughput and average delay of the network are measured using TSCH-SIM simulator.

By network throughput, we define this as the total

Table 5: Simulation parameters used for the TSCH DE optimized schedule.

Parameter	Value
SIMULATION_DURATION	2500 sec
APP_WARMUP_PERIOD_SECOND	1000 sec
LINK_MODEL	Logistic Loss model
TRANSMIT_RANGE_M	40 meters
APP_PACKET_SIZE	100
MAC_MAX_RETRIES	7
MAC_QUEUE_SIZE	15
ROUTING_ALGORITHM	ManualRouting
SCHEDULING_ALGORITHM	ManualScheduler
SLOT_FRAME_LENGTH	15
TIME_SLOT_DURATION	10 ms

number of packets successfully received at the root node in a given time and one would expect this to be the sum of all the data packet generation rates. The mathematical expression for throughout is specified as below.

$$Overall\ throughput = \frac{\sum_{i=1}^{N} received\ packets_i}{total\ simulation\ time} \quad (4)$$

where N denotes the total number of packets and $received\ packets_i$ is the number of packets received by sensor S_i.

Network delay refers to the total time (propagation, transmission, queuing, and processing period) a packet takes to travel from a source node to a destination node and it is estimated in seconds. In this simulator, the delay is evaluated by taking the difference between the time a packet is generated and is successfully received by the root node. The average delay has been calculated utilizing Equation 5.

$$Delay = \frac{\sum_{i=1}^{N} (time(i)_{received} - time(i)_{generated})}{total\ packets} \quad (5)$$

We manually configured the network with the nodes' positions, connections and routes shown in Figure 4. These values match those used to determine the optimal schedule. We chose the Logistic Loss model as the radio propagation model. For the experiment, we considered five channel offsets and 15 time slots with each time slot duration of 10 milliseconds again matching the settings and results obtained from the customized DE optimization in Matlab. The details of the simulation parameters are listed in Table 5.

In table 5, APP_WARMUP_PERIOD_SECOND is the time period it takes for all the sensor nodes to join the network (i.e when the network is stable). Data packets are not generated before this warm-up period has ended after the start of the simulation resulting in more accurate metrics. The MAC re-transmissions were left as the default value of 7, however, the MAC queue size was increased to 15 to eliminate packets being dropped from queue overflows. Simulation time was set to 2500 seconds which 1000 seconds of this time is the warm up period. Application packet size was considered as 100 bytes and the standard value for time slot was used as 10 ms. The optimal slotframe size for the schedule was obtained as 15 time slots which implies 150 ms.

Table 6: Analysis of the proposed customized DE optimization algorithm.

Evaluation Parameters	Customized DE Algorithm
PDR	99.75%
Total Generated Packets	22349
Received Packets	22295
Average Delay (sec)	3.2
Maximum Delay	4
Minimum Delay	2.4
Throughput	14.1

5.1 Simulation Results

We used the overall throughput, average end-to-end delay, Packet Delivery Ratio (PDR) as metrics to confirm the efficiency of the proposed approach. According to the results given in Table 6, it can be stated that 99.75% of the packets have been delivered successfully, although a few of the scheduled packets were lost. We noticed that some transmissions are scheduled before packet generation and due to queue overflow, the packet was lost.

As shown in table 6, the average end-to-end packet delay from the source to the root node is about 3.2 seconds. Additionally, the maximum delay and minimum delays are extracted as 4 and 2.4, respectively.

The PDR value is very high and that implied the fact that the schedule is reliable and due to considering possible collisions and inferences, majority of packets are being delivered successfully. Although other factors such as link loss can cause packet loss while increasing the simulation time.

6 TIME COMPLEXITY ANALYSIS

Time complexity is defined as the amount of time taken by the algorithm to run and find an optimal solution. The optimal solution for the optimization in this paper is the TSCH schedule with minimal slotframe size that can encompass the required transmissions.

Two main parameters were measured as complexity evaluation parameters. The first one is the $Time$ required for the algorithm to find a schedule to satisfy all the node's throughput. The second evaluation parameter is L_{sf} that denotes the slotframe length of the discovered optimal schedule. It is important to know how many time slots used in the schedule to satisfy all the nodes. The parameters that were modified to analyse the performance of the Customized DE optimizer are N; the total number of nodes in the network and I_{max}; the maximum iteration of optimization process for each slotframe size.

Two complexity cases were defined, Case 1 and Case 2. The difference between complexity Case 1 and Case 2 is the packet rate of the nodes. The packet rate of the nodes is defined to be a value between 0.1 and 1 packets/sec in Case 1 while packet rates higher than 1 packets/sec is used for Case 2. For each case there were different groups of scenarios created where various typologies and packet rate were used, however, for each group of scenarios the average number of neighbors Avg_{NBR} and the depth of the tree D were kept identical. The objective of this analysis is to observe the impact of the iteration in the optimization process as well as the effectiveness of number of nodes, packet rate and maximum iteration value on the time complexity of the algorithm.

6.1 Complexity Case 1

In Complexity Case 1, the packet rate of the nodes were specified as random values between 0.1 and 1. We implemented four different scenarios as 1, 2, 3 and 4 for an in-depth performance analysis and the specification of each scenario is presented in Table 7.

Table 7: Summary of eight scenarios for applications with data rate of less than 1 packet per second.

	N	I_{max}	L_{sf}	Avg_{NBR}	D	$Time(s)$
SCN 1-1	10	20	10	2	4	37.79
SCN 1-2	10	50	9	2	4	77.57
SCN 2-1	14	20	16	3	5	97.68
SCN 2-2	14	50	15	3	5	246.89
SCN 3-1	25	20	32	3	5	877.59
SCN 3-2	25	50	29	3	5	1013.57
SCN 4-1	50	20	52	4	10	1154.32
SCN 4-2	50	50	47	4	10	12940.62

The goal is to prove that the Customized DE optimization algorithm can find a solution for different sizes of networks with heterogeneous data rates and have an estimate of time complexity. The first two scenarios, SCN 1-1 and SCN 1-2 represent a small network consisting of 10 nodes. The difference between these two scenarios is the maximum number of iterations (I_{max}); which is considered as 20 and 50 in SCN 1-1 and SCN 1-2, respectively. I_{max} denotes the maximum number of iteration in optimization process for each slotframe length. Providing that I_{max} is equal to 20 and starting from the slotframe size of 3, the algorithm iterates 20 times maximally and after analyzing the population fitness value, if the populated schedule does not meet the requirement of the objective function (which is satisfying all nodes), it will increase the slotframe size by one and then after resetting the I_{max} value, it continues the optimization process. Otherwise, it will terminate the algorithm with the optimal schedule as the solution. The average number of neighbors in SCN 1-1 and SCN 1-2 was 2 and the depth of the Tree structure was kept as a static number of 4. The next three scenarios are Networks including 14, 25 and 50 nodes with the given parameters as the average number of nodes (Avg_{NBR}) and the depth of the tree (D).

As it can be observed from the results shown in Table 7, the algorithm is able to find a solution for 4 different sizes of network . The optimal solutions obtained for SCN 1-1 and 1-2 were schedules with slotframe sizes of 10 and 9, respectively. While the maximum iteration I_{max} is set to a larger value for SCN 1-2 it was able to find an optimized schedule with smaller slotframe size. This is important as the time complexity grows by increasing the maximum number of iterations, I_{max}, and the number of the nodes N.

As the number of nodes increases in the network, the maximum iteration value has to be increased for the optimizer to find a solution. It can be seen in table 7 that although the simulation specifications such as number of nodes, average number of neighbors and depth of the tree are identical, the slotframe size of the schedule found for I_{max}=20 is typically higher than for I_{max}=50 since there are more iterations and hence more populations generated to find an optimal schedule. In SCN 1 and SCN 2, the difference between slotframe size of I_{max}=20 and I_{max}=50 is only one slotframe; however, for the next two scenarios SCN 3 and SCN 4, the gap between I_{max}=20 and I_{max}=50 is 3 and 4, respectively. It can be concluded that for higher number of nodes, choosing a larger value for I_{max} results in schedules with smaller slotframe size and consequently less delay though the time to achieve this increases exponentially.

We also observed that for packet rate of less than 1 the total number of required transmissions was constant at 18. This makes the optimization simpler as the objective value (number of transmissions) does not change. However one will see, in the next section, that this value will grow more by increasing the slotframe length in networks with higher packet rates.

6.2 Complexity Case 2

In Complexity Case 2, we increased the packet rates to random values larger than 1 packet/sec to analyse the performance of the algorithm in high packet rates. Four different scenarios as SCN 5, SCN 6, SCN 7 and SCN 8 were considered and the specification of each scenario is illustrated in Table 8. The number of nodes in SCN 5 to SCN 8 was set to 10, 14, 25 and 50 nodes, respectively. Each scenario was implemented in two different values for I_{max} as 20 and 50. For each scenario, the values of time complexity and the slotframe length of the optimal schedule were measured to discover the impact of the number of nodes and value of I_{max} on time complexity and slotframe length (L_{sf}).

Table 8: Summary of eight scenarios for applications with packet rate more than 1 packet per second.

	N	I_{max}	L_{sf}	Avg_{NBR}	D	$Time(s)$
SCN 5-1	10	20	26	2	4	432.46
SCN 5-2	10	50	25	2	4	1120.72
SCN 6-1	14	20	40	3	5	1736.83
SCN 6-2	14	50	37	3	5	4254.37
SCN 7-1	25	20	57	3	5	3407.36
SCN 7-2	25	50	51	3	5	9127.91
SCN 8-1	50	20	86	4	10	12201.45
SCN 8-2	50	50	75	4	10	24055.78

Although according to Table 8, it will take more time to find a solution compared to the scenarios in Case 1, the proposed customized DE optimizer was able to discover a schedule for heterogeneous network having higher packet rates that were greater than 1 packet per second.

As mentioned in the previous section, when the network has to satisfy higher data rates the expected number of transmissions climbs considerably due to the slotframe length increment and the high packet rate of nodes. Figure 6 shows an example of this increase in the expected number of transmissions for the case of a topology consisting of 10 sensor nodes and a range of slotframes between 3 to 10. The expected number of transmissions climbs considerably due to the slotframe length (which basically increases the time of the slotframe) and the high packet rate of the nodes. At higher slotframe lengths, the nodes generate more packets, as a consequence, the associated number of required transmissions grows accordingly and the assigned number of slots is not sufficient anymore.

The figure also shows the number of satisfied nodes in each slotframe length as the optimization progresses. The optimization will continue until the number of transmissions is satisfied by all the nodes in the network, which in this example topology is 10.

We illustrated a portion of the optimization process only as the solution a slotframe size of 25 or 26 depending on the maximum number of iterations.

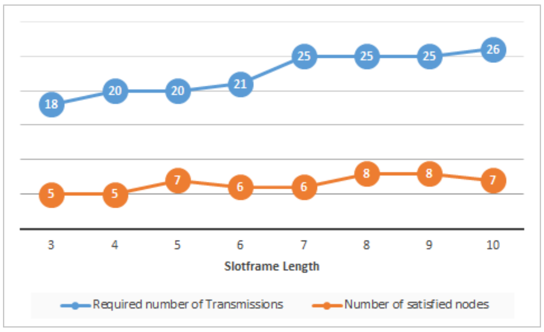


Figure 6: Total number of required transmissions in slotframe length between 3 and 15 for packet rate higher than 1 packet/sec and the number of satisfied nodes.

6.3 Analysis of over Scheduling

The schedule that is created by the optimization algorithm is a conservative schedule with more slots scheduled than required due to the round up of the number of required transmissions. The advantage of over scheduling is that the schedule is less susceptible to data losses because there are extra time slots scheduled to accommodate for the re-transmission of the data. The drawback of over scheduling can be higher energy consumption as the time slot will consume more energy if scheduled to transit or receive than if it is in an idle mode.

We calculated the average of the total number of required transmissions of each node for a network topology of 10 nodes for different slotframe sizes ranging from 3 to 15 and compared this to the number that was scheduled. The results are depicted in Figure 7. The average percentage of overscheduling is 11.6 % for this scenario.

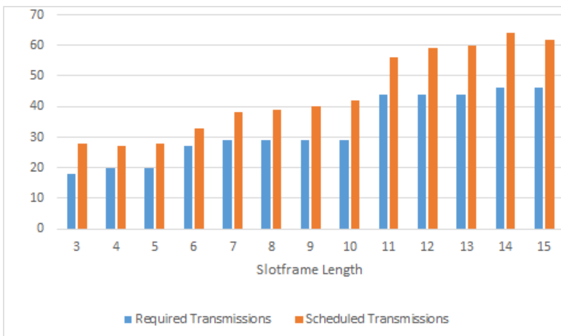


Figure 7: Total number of required transmissions vs. assigned number of transmissions for slotframe length between 3 and 15 for a network consisting of 10 nodes.

7 CONCLUSION

In this paper we proposed a novel slotframe length optimization approach using a customized DE optimization algorithm that considers possible packet collisions and interference. It also supports different packet generation rates. The presented method finds a schedule with minimum slotframe length which will minimize the average delay in the network. The performance analysis using the TSCH-Sim simulator confirm that the DE optimized schedule is working without any collision and interference. We conducted several experiments using different scenarios to analyse the performance of the algorithm.

As future work, we are planning to include an adaptive component to the scheduler that can react to changes in the routes of the network as the current static schedule is not ideal as it assumes a static route. It is also worth investigating how much further can the schedule be optimized since the current approach results in an over-scheduled solution which can result in scheduled cells that are not being utilized although it helps to transmit all the packets generated successfully in case there is a packet loss due to the unexpected conditions.

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