Optimization of Multi-token Circulation with Master UAV Method in Multi-UAV Systems for Location Information Sharing

Eyup Emre ULKU
Department of Computer Engineering, Marmara University
Faculty of Technology, Goztepe Campus/34722
Kadikoy-Istanbul, Turkey
emre.ulku@marmara.edu.tr

Ilayda ULKU
Department of Industrial Engineering, Istanbul Kultur University Faculty of Engineering, Atakoy Campus/34156
Bakirkoy-Istanbul, Turkey
i.karabulut@iku.edu.tr

***Abstract*— In order to perform smooth and coordinated flights in multi-UAV systems, UAVs (Unmanned Aerial Vehicle) need to know each other's location information. Multi-token circulation method allows UAVs to learn each other's location information in the Flying Ad Hoc Network (FANET) quickly and this information can be updated continuously. In the multi-token circulation method, it is very important to determine how many tokens are used and how these tokens circulate in the FANET depending on the number and deployment of the UAVs. In this paper, we developed a master UAV method to determine number of tokens and circulation of these tokens.**

Keywords— unmanned aerial vehicle (UAV); multi UAV systems; flying ad hoc networks (FANET); multi-token circulation; location information sharing; vehicle routing problem (VRP).

I. Introduction

Autonomous vehicles are defined as self-acting vehicles without the need for a driver [1]. Unmanned aerial vehicles (UAV) is a widely used type of autonomous vehicles. [2]. In recent years with advances in UAV technologies, multi-UAV systems in other words UAV swarms that consist of a large number of UAVs has become increasingly widespread and the use of these systems is increasing day by day [3]. With this prevalence, the concept of multi-UAV is becoming a more popular research topic [4]. Many military and civilian tasks can be carried out in a much shorter time with much higher performance without risking human life by the multi-UAV systems [5]. These mentioned benefits play a leading role in the widespread use of UAVs. Thanks to the wide spread of UAV swarms, tasks such as target search [6], monitoring and viewing of a region [7], delivering aid to a region, and post-disaster planning [8] can be completed in a shorter time with high performance.

Although there are many advantages of using multi-UAV systems, it is becoming increasingly complicated to provide coordination of UAVs within the swarm. There is a need for a robust system to ensure the coordination of multi-UAV systems to provide efficient and smooth communication between UAVs.

Even though infrastructure based approach is a widely used method in communication between UAVs, it has led to the search for alternative solutions due to the limited communication range and the fact that infrastructure cannot be provided in all cases [9]. The concept of flying ad hoc network (FANET) provides an important solution in the enabling of communication in multi-UAV systems without the need for an infrastructure [10]. The second step that should be taken after the communication is provided with the FANET structure in order to carry out coordinated flights in multi-UAV systems is to ensure that the UAVs need each other's rapidly changing location information to make coordinated and trouble-free flights.

A multi-token based method that tokens holding location information of the UAVs in the multi-UAV systems has created a structure to enable UAVs to know each other's position with the least error. The coordinates information of all UAVs are kept in the tokens. The tokens move between the UAVs depending on the communication range, and by comparing the information they hold during the roaming and the information in the UAVs' memory, they update both their own information and the information that the UAVs hold. With the increase of the number of UAVs, the number of UAVs to be visited and the size of the coordinate information to be kept in the tokens increase. Because of this condition, the tokens circulation times are extended. In order to avoid this situation, the number of tokens in circulation has been increased. In the studies conducted with multi-token circulation method, it has been tried to show the effectiveness of the method by trying a different number of tokens with different numbers of UAVs [3, 11, 12]. At this point, according to the structure of the multi-UAV system, there is a need for a model to determine the number of tokens and how they circulate to collision.

As an indispensable mission assignment for UAVs there is an increasing attention on researching the path between the UAVs. To determine the number of UAVs in the network, what is the best route for every UAV in order to minimize the travel distance, how long will it take to accomplish the task are common problems that are studied in the literature [13-16]. To solve the multi-token circulation in multi-UAV systems we propose the vehicle routing problem (VRP) which is known as an operational research problem. The token is considered as a vehicle with the mission to visit all UAVs. In this paper, we developed a mathematical model to determine number of tokens to provide sharing of location information between the UAVs. Simultaneously, the route for each token is determined with the proposed model. Total distance travelled and time used for the circulation is determined. The problem is modeled as a mixed integer linear program and optimal solutions are obtained. Using the proposed model a set of test instances are illustrated. The experiments show that the instances can be optimized for 5 UAVs with 1 token, for 10 and 15 UAVs 2 tokens, and for 20 and 25 UAVs 3 tokens are needed.

In the developed algorithm, the substitute master UAV structure has been added to the algorithm to ensure that the multi-UAV system continues to operate smoothly. Thus, with the dynamically changing master-substitute master structure, the continuity of the autonomous structure provided to the multi-UAV system has been ensured.

The organization of the paper is as follows. In Section 2, multi-token circulation with master UAV method is defined and proposed mixed integer programming model is presented. Experimental study of the proposed model is stated in Section 3 and Section 4 concludes the paper.

II. MULTI-TOKEN CIRCULATION WITH MASTER UAV METHOD

The UAVs in FANET, which have the ability to move quickly, need a structure to keep each other's constantly changing position information up to date. In the token based approach, the location information of the UAVs is kept in the token and the token constantly visits all UAVs to update the location information of both its own memory and the UAVs. In this way, it is ensured that UAVs in the multi-UAV system are able to learn each other's constantly changing position information quickly [11, 12]. With the increase of the number of UAVs, the size of the position information to be carried by the token and the number of UAVs that the token should visit also increase. Due to this reason, token circulation time in FANET is extended. Extension of the circulation time delays the UAVs learning the current position information of each other. In order to avoid this situation, multi-token circulation based system is recommended in the studies [3, 11, 12]. In these systems, the number of tokens in circulation is increased with the increasing number of UAVs. With the increase in the number of tokens, the UAVs are provided to learn each other's location information quickly.

However, when more than one token is in circulation in FANET, the probability of collisions of the tokens is a problem to be solved. The allocation of a separate communication channel for each token prevents the token collisions, but is an inefficient, cost-effective method [3, 11]. In the two-channel token circulation model, there are two communication channels independent of the number of token and in one of these channels the tokens are circulated and the other channel transmits routing packets that allow tokens to avoid collisions [12, 17]. The two-channel model prevents token collisions. In the studies where this model is proposed, the results of different number of tokens for different numbers of UAVs have been tested [12, 17].

In this study, the proposed master UAV method decides how many tokens in the FANET circulate and the route in which the tokens move, depending on the number of UAVs and the deployment of UAVs. Thus, the token number and circulation are optimized by master UAV and an autonomous structure is provided for the multi-UAV systems.

Information about the structure and the content of the tokens is shown in Fig. 1. There are four different fields in the token format, including the token ID, the token's roaming route, the substitute master UAV list and the coordinate information of the all UAVs. Since there may be more than one token circulating in the FANET, there is a unique token number in the first field of the token that allows the tokens to be separated from each other. In the second field, there is information indicating the route of the token's circulation. With this information, the token knows which UAVs will be visited by which order. In the third area, if the master UAV is not accessible or the master UAV is disabled, a list of the substitute master UAVs that can be master UAVs is kept. This list is also kept in a priority order of the master UAV candidates. The last field includes the coordinate information of all UAVs and the counter variable to be used to compare the up to dateness of the coordinate information.

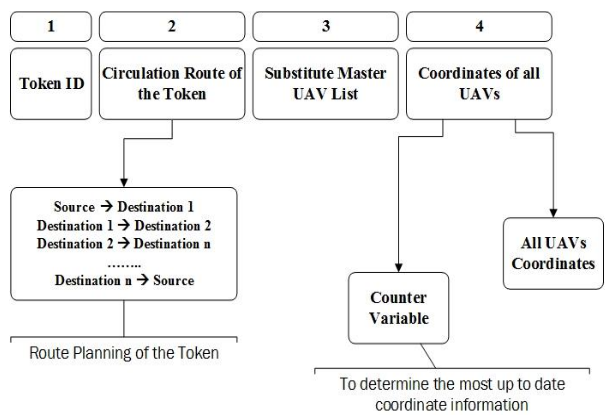


Fig. 1. Token format

Once the token format to be used for the UAVs to learn each other's location information has been determined, in the second phase should designate how these tokens circulate in the FANET. In order to ensure non-collision token circulation within the FANET, the most appropriate number of token and the path to be followed by the tokens are performed autonomously by the master UAV method.

Traveling salesman problem (TSP) is represented as a graph where the locations and the routes between the locations are represented with nodes and edges, respectively. The distance between the nodes is represented as the weight of each edge. Thus, the aim is to determine shortest sum of the weights that is the route between the locations. A generalization form of

TSP is the Vehicle Routing Problem (VRP) where the aim is to determine the optimal set of routes for vehicles delivering goods or services to various locations from a single place of origin, a depot [18]. Therefore, the token in the network are represented as vehicle, the UAVs are used as locations to be visited by the token, and the depot is represented as Master UAV in the network. As, TSP is an NP-hard problem [19], multi-token circulation in multi-UAV systems for location information sharing is a combinatorial optimization problem.

How the UAVs keep the location information of other UAVs up to date through to the tokens circulating in the FANET is shown in the pseudo code in Fig. 2. The information update process repeats for each token as much as the number of tokens determined by the Master UAV. The UAV that receives the token compares the information in the token and in its own memory and updates the information in both its own memory and the token. The other neighbors of the source UAV who overhear the token because they are within the communication range, can update the information in their own memory even if they cannot update the token. The update process is provided by the counter variable included with the location information. The counter variable is incremented at every unit time so that the position information with the highest counter value is the most up to date information.

```
while (UAVMove! = 0) do
    i ← 1;
    NumberOfTokens ← MasterUAV.TokenNumber;
    while (i <= NumberOfTokens) do
        for j ← 1 to list.lenght do
            if (Token(i).destination == ThisUAV) then
                UAVCacheMemory ←
                  (UpdateCache(UAVCacheMemory, Token(i));
                Token(i) ←
                  UpdateToken(UAVCacheMemory, Token(i));
            end if
            UAVCacheMemory ←
              UpdateCache(UAVCacheMemory, Token(i));
        end for
    end while
end while
```

Fig. 2. Pseudo Code for multi-token circulation.

A. Proposed Mixed Integer Programming Model

In order to collect location information from the UAVs and share the data immediately to the rest of the UAVs is an important purpose in the multi-UAV systems.

Let $G = (V, E)$ be an undirected and connected graph where V is the set of identical UAVs and E is the set of edges between nodes that is the set of token connection between each pair of UAVs. The coordinates (x_i, y_i) of the UAVs are randomly placed. Location of the UAVs and master UAV is also known a priori. Master UAV is determined according to the most neighboring UAV in the network.

Connectivity assumption for the multi-UAV Systems is based on the Euclidean distance between UAVs, denoted as d_{ij} as represented in (1) where $i, j \in I$. If distance between UAV connections is less than the communication range, then the connection between UAVs may be considered as possible connection.

$$d_{ij} = (x_j - x_i)^2 + (y_j - y_i)^2 \tag{1}$$

Test instances are generated in Section III and the parameters of the problem are listed in Table 1. Since, the terrain dimensions are used as 2200 m x 2200 m, the communication range differs according to the number of UAVs in the terrain dimensions. Due to the transmission time is much longer than the processing time, the processing time is negligible when taken together with the transmission time [20]. For this reason, it is aimed to minimize the token circulation time with the algorithm developed in the study.

TABLE I. SELECTED PARAMETERS FOR THE EXPERIMENTAL STUDIES

Parameter	*Value*
1. Terrain dimensions	2200 m x 2200 m
2. UAV Speed, v	5 m/s
3. Number of UAVs	(5, 10, 15, 20, 25)
4. Communication Range for each UAV instances	For 5 UAVs →400 m For 10 UAVs →425 m For 15 UAVs →225 m For 20 UAVs →400 m For 25 UAVs →290 m
5. Flight Topology	Grid Topology
6. Channel Transmission Speed	11 Mbps (Megabit per second)
7. Channel Type	Channel/Wireless Channel
8. MAC Type	Mac/802.11
9. Daily Time Limit (sec.), dtl	3000 seconds
10. Delivery time of location information distributed to UAVs (sec), d_t	0.001

Finally, decision variables of the problem are as follows:

$$U_{ij} = \begin{cases} 1, \text{ if location j is visited after location i} \\ 0, \text{ otherwise} \end{cases}$$

TS_{ij} = Total time spent while moving from location i to location j (sec)

The aim of the mixed integer programming model for the proposed master UAV method is to search for a feasible route plan, in order to minimize the total time t_{ij} as shown in (2) where UAV speed is assumed to be 5 m/s to determine $t_{ij} = d_{ij} / v$ to visit all the UAVs in the network.

$$\min \sum_{i=1}^{I} \sum_{j=1}^{J} t_{ij} * U_{ij} \tag{2}$$

Each UAV in the network should have exactly one incoming edge and one outgoing edge as represented in (3) and (4).

$$\sum_{\substack{j=1 \\ j\neq i}}^{J} U_{ji} + U_{Master,i} = 1, \qquad \forall i \tag{3}$$

$$\sum_{\substack{j=1 \\ j\neq i}}^{J} U_{ij} + U_{i,Master} = 1, \qquad \forall i \tag{4}$$

Equation (5) defines unidirectional constraint. Equation (6) is used to prevent cycling between each UAV pair.

$$\sum_{\substack{j=1 \\ j\neq i}}^{J} U_{ij} = \sum_{\substack{j=1 \\ j\neq i}}^{J} U_{ji}, \qquad \forall i \tag{5}$$

$$U_{ij} + U_{ji} \leq 1, \qquad \forall i,\ j,\ i \neq j \tag{6}$$

Cumulative time spent of UAV i in the network is determined with (7). Total travelling time of each UAV is ensured in (8) that does not exceed the maximum traveling time. Also, in (9), total distance travelled by a UAV is restricted with daily time limit for each UAV.

$$\sum_{\substack{j=1 \\ j\neq i}}^{J} TTS_{ij} = \sum_{\substack{j=1 \\ j\neq i}}^{J} TTS_{ji} + \left[U_{ij} * (d_t + t_{ij})\right], \qquad \forall i, \quad i \neq Master \tag{7}$$

$$(d_t + t_{ij}) * U_{ij} \leq TS_{ij}, \qquad \forall i, j, \quad i \neq j \tag{8}$$

$$TTS_{ij} \leq dtl - d_t - (t_{ij} * U_{ij}), \qquad \forall i, \quad i \neq j \tag{9}$$

Equation (10) and (11) guarantees the binary requirements and non-negativity of the variables.

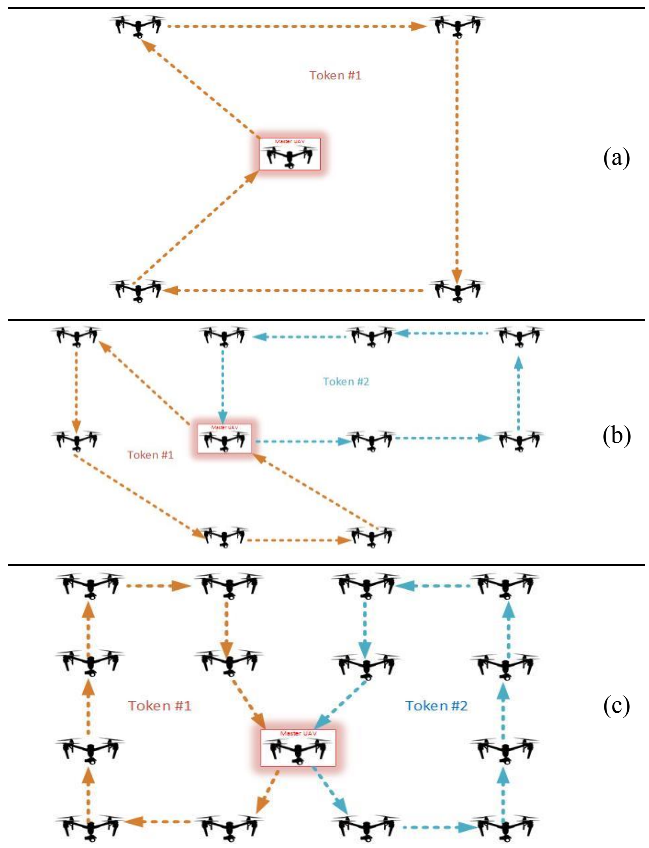
$$U_{ij} \in \{0,1\}, \qquad \forall i, j \tag{10}$$

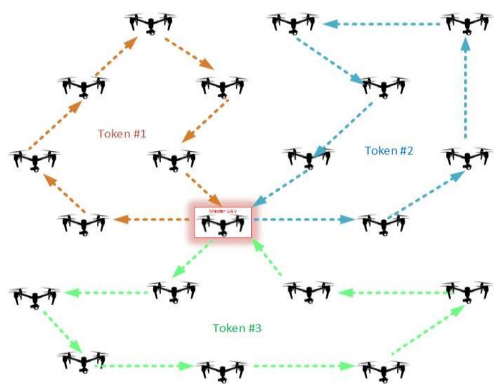
$$TTS_{ij}, \qquad \forall i,\ j \tag{11}$$

III. Experimental Study

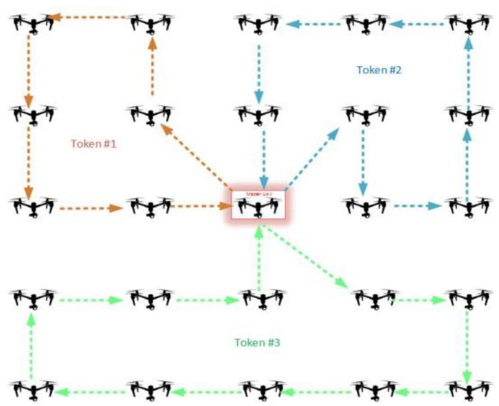
In this section, to show the effectiveness of the proposed mixed integer model the results of computational experiments are presented to optimize the multi-token circulation with Master UAV Method in multi-UAV systems for location information sharing. GAMS software package with CPLEX solver [21] is used and the runs are executed on a 4.20 GHz Intel Core i7 computer with 32 GB of RAM.

In Fig. 3 the performance evaluation of the proposed algorithm is presented. The UAVs in FANET are deployed in the terrain, according to the highest number of neighborhoods for the grid topology sequence. In accordance with the output results, for the deployment of 5 UAVs there is 1 token used with the 400 m communication range to share the location information. When the UAV number is increased to 10, the required number of tokens are increased to 2. As the UAV obtain the information via token, the information is compared and its memory is updated unless it is the same with the token information. If there is only one token, the information update time will be extended as the number of the UAVs are increased in the terrain dimension. Moreover, the UAVs may lose communication because they may lose each other due to the single token circulation in the system. For 15, 20, and 25 number of UAVs in the network there are 3 tokens needed to obtain adequate location information to optimize the multi-token circulation with Master UAV Method in multi-UAV systems. The performance of the developed algorithm has been implemented on different UAV numbers to show that the algorithm can be applied for multi-UAV systems with a different number of UAVs.





(d)



(e)

Fig. 3. Experimental results (a) 5 UAVs (b) 10 UAVs (c) 15 UAVs (d) 20 UAVs (e) 25 UAVs.

It is obvious that not only the communication range but also the number of UAVs are critical parameters to solve the problem. With the developed master UAV method, UAVs are able to update each other's location information as soon as possible. In addition, the tokens' routes are determined by the master UAV allow the tokens to circulate without collision.

IV. CONCLUSION

In this study, with the proposed master UAV method we have stated the necessary number of tokens in the FANET to share the location information between the UAVs.

With the proposed master UAV approach, different deployment scenarios are generated and the results are satisfactory. Simultaneously, the related route for each token is determined according to the number of master UAVs and the deployment of UAVs in the network. The number of tokens and circulation in the network are optimized by master UAV and an autonomous structure is provided for the multi-UAV systems. The ability of the tokens to perform their circulation without collision also enabled all UAVs to quickly update the location information of other UAVs. The obtained results indicate the effectiveness of the master UAV method for location information sharing of UAVs in the multi-UAV systems.

As a future study, we are planning to extend our model as including the third dimension for the deployment of UAVs that is one of the key challenges to obtain communication between UAVS. Then, it is aimed to apply the method developed in this study to larger multi-UAV systems. Moreover, it is planned that the UAVs carry the image data as a load and the load is collected in the most optimized way in a center by the master UAV method.

ACKNOWLEDGMENT

Participation in this conference was supported under grant FEN-D-120619-0205 by Marmara University Scientific Research Unit.

REFERENCES

[1] H. Hastie, X. Liu, Y. Petillot, and P. Patron, "Talking autonomous vehicles: Automatic AUV mission analysis in natural language", OCEANS 2017 Conference, 19-22 June 2017, Aberdeen, Scotland.

[2] O. Bouachir, A. Abrassart, F. Garcia, and N. Larrieu, "A mobility model for UAV ad hoc network", in Int. Conf. Unmanned Aircraft Systems (ICUAS), 27-30 May 2014, Orlando, FL, USA.

[3] E. E. Ulku, I. Bekmezci, "Multi Token Based Location Sharing for Multi UAV Systems", International Journal of Computer and Electrical Engineering, vol. 8, pp. 197-206, 2016.

[4] C. Nami, K. Oka, and A. Harada, "H∞ structured controller synthesis applied to flight controller of QTW-UAV using meta-heuristic particle swarm optimization", Proceedings of the SICE Annual Conference, pp. 643-648, 20-23 September 2016, Tsukuba, Japan.

[5] Z. Xueping, L. Zhengchum, and J. Yang, "Model of collaborative UAV swarm toward coordination and control mechanisms study", Procedia Computer Science, vol. 51, pp. 493-502, 2015.

[6] H. Xiaoxuan, L. Yanhong, and W. Guoqiang, " Optimal search for moving targets with sensing capabilities using multiple UAVs", Journal of Systems Engineering and Electronics, vol. 28, p. 526-535, 2017.

[7] C. Feng, S. Yuejun, Z. Shoudong, L. Jonathan, W. Cheng, and Z. Xudong, "Preliminary comparison of the multispectral cameras onboard UAV platform for environment monitoring", 26th International conference on Geoinformatics, 28-30 June 2018, Kunming, China.

[8] Z. Shangwei, L. Jiajia, "Analysis and Optimization of multiple unmanned aerial vehicle-assisted communications in post-disaster areas", IEEE Transactions on Vehicular Technology, vol. 67, p. 12049-12060, 2018.

[9] E. A. Marconato, J. A. Maxa, and A. S. R. Pinto, "IEEE 802.11n vs. IEEE 802.15.4: a study on communication QoS to provide safe FANETs", 46th Annual IEEE/IFIP International Conference on Dependable Systems and Networks Workshops, 28 June – 1 July 2016, Toulouse, France.

[10] I. Bekmezci, O. K. Sahingoz, S. Temel, "Flying ad-hoc networks (FANETS): a survey", Ad Hoc Networks, vol. 11, no. 3, pp. 1254–1270, 2013.

[11] I. Bekmezci, E. E. Ulku, "Location information sharing with multi token circulation in flying ad hoc networks", 7th Int. Conf. Recent Advances in Space Technologies (RAST), 16-19 June 2015, Istanbul, Turkey.

[12] E. E. Ulku, B. Dogan, O. Demir, and I. Bekmezci, "Sharing location information in multi-UAV systems by comman channel multi-token circulation method in FANETs", ELEKTRONIKA IR ELEKTROTECHNIKA, vol. 25, no.1, pp. 66-71, 2019.

[13] N. Agatz, P. Bouman, and M. Schmidt, "Optimization approaches for the traveling salesman problem with drone, ERIM Report Series Reference No. ERS-2015-011-LIS, 27 June 2016.

[14] I. Bekmezci, M. Ermis, and S. Kaplan, "Connected multi UAV task planning for flying ad hoc networks, IEEE International Black Sea

Conference on Communications and Networking, 27-30 May 2014, Odessa, Ukraine.

[15] K. Yu, A. K. Budhiraja, and P. Tokekar, “Algorithms for routing of unmanned aerial vehicles with mobile recharging stations and for package delivery”, unpublished

[16] X. Wang, S. Poikonen, and B. Golden, “The vehicle routing problem with drones”, Journal of Applied Genetics, vol. 11, pp. 679–697, April 2017.

[17] E. E. Ulku, I. Bekmezci, “Multi token circulation in a common channel for location information sharing in multi-UAV systems”, Int. Conf. Engineering and Natural Science (ICENS), Sarajevo, Bosnia and Herzegovina,2016.

[18] G.B. Dantzig, and J.H. Ramser, “The truck dispatching problem.”, Management Science, vol. 6, no. 1, pp. 80-91, 1959.

[19] J. K. Lenstra, and A. H. G. R. Kan, “Complexity of vehicle routing and scheduling problems”, Networks, vol. 11, no. 2, pp. 221–227, 1981.

[20] S. Kakad., P. Sarode, and J. W. Bakal, “A survey on query response time optimization approaches for reliable data communication in wireless sensor network.”, International Journal of Wireless Communications and Networking Technologies, 1(2), 2012.

[21] GAMS Development Corporation. General Algebraic Modeling System (GAMS) Release 26.1.0. Washington, DC, USA, 2019.