Simulation of wireless sensors in collective motion

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***Abstract*—Wireless sensor networks (WSN) are considered to be a promising concept for enabling numerous categories of applications for both civil and military applications. This can include dismounted soldiers teams, group of animals or a group of mobile robots, where agents are moving collectively and sharing the same goal (e.g., destination, source of food or location of enemy). In this paper, we investigate the impact of dynamic agents based on a flock mobility model on the efficiency of wireless communications. We consider N mobile sensor agents capable of sensing and sending data packets periodically towards a base station (leader agent) directly or via intermediate nodes (relay nodes). At each time period, a sensor node can verify if an event is sensed based on a probability approach and then generates a data packet that is to be sent towards the destination, or else a sensor node can act as a relay node to forward data packets from other nodes. We evaluate the performance of the sensor nodes network under varying levels of perturbation of the collective motion of agents. The performance metrics observed are the residual energy, the number of sensors nodes still alive, the average normalized velocity, the packet delivery ratio, the end-to-end delay, and the average number of hops. Simulation results confirm that the dynamic agents have a significant impact on both the sensor network lifetime and the reachability of communications.**

***Index Terms*—Wireless sensor networks, Ad hoc networks, Mobility, flocking, Energy efficient WSNs.**

I. Introduction

A wireless sensor network is a group of multiple detection stations called sensor nodes. Every sensor node is equipped with a transducer, microcomputer, transceiver and power source. The transducer generates electrical signals based on sensed physical effects and phenomena. The microcomputer processes and stores the sensor output. The power for each sensor node is derived from a battery.

Many applications for wireless sensor networks are proposed in different application fields [1]; however these applications are almost limitless, with requirements such as reliability, battery-life, range, frequencies, topologies, size of the network and sensor types. Wireless sensor networks are formed by small sensor nodes communicating over wireless links without using a fixed network infrastructure. Sensor nodes have a limited transmission range, and their processing and storage capabilities as well as their energy resources are also limited. There have been many attempts to improve the efficiency of wireless sensor networks in terms of energy consumption by introducing varying protocols. These protocols can be classified into three classes. Protocols in the first class make routing decisions based on residual energy. These protocols are known as clustering-based protocols, where sensors are distributed into a number of clusters capable of communicating the detected events to a central location. A clustering-based protocol can utilize the randomized rotation of local cluster base stations (cluster-heads) to evenly distribute the energy load among the sensors in the network. This method can provides scalability and robustness by incorporating the collected data within each cluster into the routing protocol to reduce the amount of information that must be transmitted to the base station. Moreover, the data collected by the cluster heads can be transmitted via single hop [2], [3] or multi-hops communications [4]. Protocols in the second class make routing decisions based on the control of the transmission power level at each node to increase network scalability [5]. This implies that the nodes choose the transmitting power level for every packet in a wireless ad hoc network. In this context, different proprieties are taken into consideration to control the transmission power, for example the solution proposed in [6], [7], a network layer protocol called COMPOW, ensures that the transmit power used by all the nodes would converge to a common power level: the lowest power level at which the network is connected. However, these types of protocol take into consideration the additional relaying burden as they use in most cases a low transmitting power level to send packets which causes an increase in number of hops and the end-to-end delay [8]. Protocols in the third class take into consideration the control of the network topology by determining which nodes should be awake to participate in the multi-hop network topology and which should remain asleep [9]–[11]. This method allows nodes to reduce energy consumption by using multi-hop communications to avoid sending large amounts of data over long distances. However, the selection of sensors which should be awake or not remain a challenging problem due to unpredictable propagation effects in the environment. This means that sensors are not able to have uniform connectivity.

In this paper, our study aims to investigate the impact of agents dynamic with the presence of perturbations on the network reliability of wireless communications. We apply different levels of perturbations to the collective motion of the group of agents [12] which may reflect the behavioral interaction of agents in a changing environment such as that found in real-world. The considered scenario is observed in different fields of sensors network applications, including for

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example that of a soldier leader who must be informed about of the health of their neighbors or a group of animals equipped with sensors which monitor their health state. Then, based on a disturbed parameter that governs the level of perturbation of the collective motion of the agents group, we monitor the dynamics of that agents group, as well as the sensor network lifetime and the reachability of wireless communications by using several performance metrics.

The paper is organized as follows. In section 2, agent-based modelling of collective motion of agents and the adopted communication network model are presented in detail. In section 3, the numerical results were reported and the occurrence reason is explained. The conclusions are given in section 4.

II. Model Descriptions

A. Mobility of agents

This section describes the considered flock mobility model specifically designed for governing the dynamics of agents in a simulation area. It illustrates how autonomous agents are able to make interaction based on a superposition of these simple rules to define different behaviors with each other, where agents carry out their tasks collectively in order to contribute to a common goal (e.g., destination or location of enemy). Accordingly, each agent is able to make interaction with other agents in its neighborhood based on three basic rules [13]–[15].

- cohesion: attempt to stay close to each other.
- separation: behavior that avoids collisions by causing an agent to steer away from all of its neighbors.
- alignment: behavior that causes a particular agent to line up with soldiers close by.

In our model we consider N agents that move at a constant speed of v_0 units per second with periodic boundary conditions. Each agent is characterized by his location $\mathbf{c}_i(t)$ and velocity $\mathbf{v}_i(t) = v_0 \times \mathbf{d}_i(t)$ of direction $\mathbf{d}_i(t)$ at time t.

In each time step t, an agent i assesses the position and/or orientation of neighbors in its local neighborhood within three

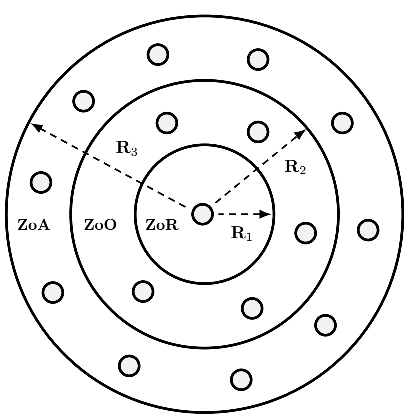

Fig. 1. Representation of a sensor node in the model with deferent behavioral zones: zor=zone of repulsion, zoo=zone of orientation, zoa=zone of attraction.

Algorithm 1 : The Flocking Model.

if $N_1 \neq 0$ **then**
  $\mathbf{d}_i(t+dt) = -\sum_{j\neq i}^{N_1} \frac{\mathbf{r}_{ij}}{|\mathbf{r}_{ij}|}$
  // Agent i responds by moving away
  // from the N_1 neighbors of ZOR.
else
  if $N_2 \neq 0$ **then**
    $\mathbf{d}_i(t+dt) = \sum_{j=1}^{N_2} \frac{\mathbf{v}_j}{|\mathbf{v}_j|}$
    // Agent i will attempt to align itself
    // with the N_2 neighbors of ZOO.
  else
    if $N_3 \neq 0$ **then**
      $\mathbf{d}_i(t+dt) = \sum_{j\neq i}^{N_1} \frac{\mathbf{r}_{ij}}{|\mathbf{r}_{ij}|}$
      // Agent i will attempt to align himself
      // towards the N_3 neighbors of ZOA.
    else
      $\mathbf{d}_i(t+dt) = \mathbf{d}_i(t)$
      // agent i does not interact.
    end if
  end if
end if

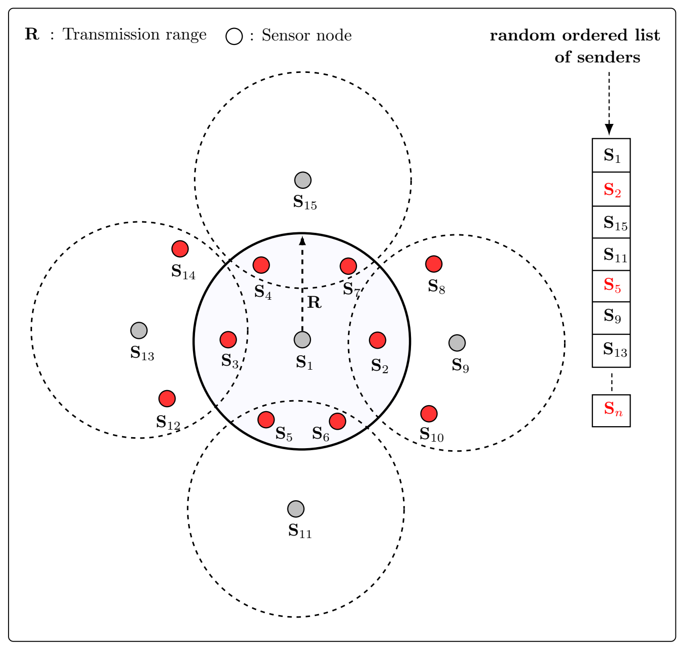

Fig. 2. Illustration example of multiple-access to wireless channel based on the proposed Mac protocol.

non-overlapping behavioral zones (Fig. 1) to determine its desired direction of motion $\mathbf{d}_i(t+dt)$ at time $t+dt$. After that, the agent i moves towards the unit vector $\mathbf{d}_i(t+dt)$ that defines the average direction of motion given based on the interaction with other agents within the corresponding zone [13]. The unit distance vector from the location point of agent

i in the direction of the agent j is given as follows:

$$\mathbf{r}_{ij} = \frac{\mathbf{c}_j - \mathbf{c}_i}{|\mathbf{c}_j - \mathbf{c}_i|} \tag{1}$$

The desired direction of motion at time $(t + dt)$ is given as follows (see Algorithm1).

After the above process has been performed for every agent i, all agents move towards the desired direction $d_i(t + dt)$ at time $(t + dt)$ as follows:

$$\mathbf{p}_i(t + dt) = \mathbf{p}_i(t) + \mathbf{d}_i(t + dt) \times v_0 \times dt \tag{2}$$

Here, we introduce a random angle α chosen uniformly from the interval $[-\frac{\eta}{2}, \frac{\eta}{2}]$ as follows:

$$\alpha = -(\frac{\eta}{2}) + rand(0, 1) * (\frac{\eta}{2}) \tag{3}$$

where η is a noise parameter specified before the simulation setup.

B. Wireless communication network model

In this section, we consider N mobile agents equipped with sensor nodes capable of communicating using short-range radio transmissions. For each pair of nodes i and j located within the transmission range R of each other, where the received signal strength at nodes i or j decays with the distance between them. This phenomenon can be described by the path-loss model [16] which defines the relationship between the signal power of the transmitting node i, the signal power received by node j (e.g., receiver node) and the distance between them, respectively. Then the signal power received by node j is given as follows:

$$\mathbf{p}_j = \frac{p_i}{c\, r_{i,j}^{\alpha}} \tag{4}$$

where $r_{i,j}$ is the Euclidean distance between agent i and j, p_i and p_j are the transmitted power and the received power, respectively, c is a constant that defines the number of factors including the transmission frequency, and α is varying parameter between 2 and 5 [17]. We use an r^2 energy loss due to channel transmission [2]. Thus, to transmit a k-bit message to node j located a distance $r_{i,j}$ from node i, the radio of node i expends:

$$\mathbf{E}_{Tx}(k, r_{i,j}) = \begin{cases} E_{ele}\, k + \epsilon_{amp}\, k\, r_{i,j}^2 & r_{i,j} < d_0 \\ E_{ele}\, k + \epsilon_{amp}\, k\, r_{i,j}^4 & r_{i,j} \geq d_0 \end{cases} \tag{5}$$

where the radio of node j, to receive the transmitted message from node i, expends:

$$\mathbf{E}_{Rx}(k, r_{i,j}) = E_{ele}\, k \tag{6}$$

On the other hand, we have assumed that at time t, node i can transmit data packet to node j if the signal power received by node j is strong enough compared to the thermal noise and interference power with other transmitters. This can be written formally as:

$$\mathbf{SNR} = \frac{p_i\, g(c_i - cj)}{\sigma^2 + \sum_{k \neq i,j}^{N} p_k\, g(c_k - cj)} \geq \beta \tag{7}$$

where SNR is the signal-to-interference ratio, β is the SNR threshold requirement for successful communication, σ^2 is the background noise power and $g(c_i - cj) = \frac{1}{c\, r_{i,j}^{\alpha}}$. The term $\sum_{k \neq i,j}^{N} p_k\, g(c_k - cj)$ is the interference contribution from nodes within the transmission range of the receiving node j.

C. Implementation of Mac protocol

Here, a simplified Mac protocol is implemented to solves the problem of multiple-access of different transmitters to a wireless channel at same time. So, our proposed Mac protocol can be used to control the multiple-access of transmitters by limiting the channel assignment only for some transmitters in the network in the following way. At each time step of simulations we create a randomly ordered list of transmitters allowed in the network. The first node on the list then gets access to the wireless channel and all transmitters which may cause interferences to that node are blocked for this time step, including those located in the transmission range of transmitter node and the receiving node (see Fig. 2). This procedure is repeated for the remaining nodes until the list is reduced to a set of non-interfering nodes which can transmit a data packet at the same time step. Fig. 2 shows that all senders nodes located in the transmission range of sender S_1 (e.g., S_2, S_3, S_4, S_5,

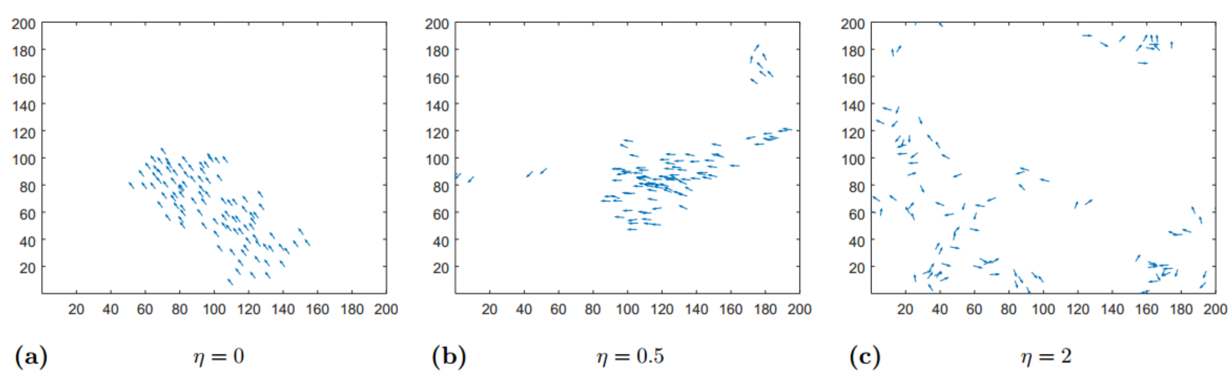

Fig. 3. Snapshot illustration of agent group condition with different values of noise η.

S_6 and S_7) are blocked at this time step, where only S_1 is allowed to broadcast a packet. The total number of authorized senders based on the random ordered list at the same time step t are marked with a gray color, whereas blocked senders are marked with a red color (e.g., S_1, S_{15}, S_{11}, S_9 and S_{13}).

D. *Queue Management*

In the following part we separate the forwarding and originating packets into two queues, where the control of rate of originating data of a sensor node is done via a probability parameter (p_s). The value of this parameter determines if an event is sensed or not at a specific step time by the sensor node. Moreover, we use a very simple policy that menages the priority issue between originating and forwarding data. With the assumption that originating data is low as compared to that of forwarding messages, we give priority to the originating traffic [18].

III. Simulation Environment

In this paper, all models have been implemented using C++ language, where a sensor network of N mobile nodes/agents deployed close to each other in a simulation area of 200×200 m^2. At each time step dt. The agents/nodes are able to send data packets towards the leader of the group (the leader is selected randomly at the beginning of simulation) based on a probabilistic approach (an event is sensed with a probability p_s). Thus, a sensor node can send an originating packet towards the destination (leader agent) or relays unrelated messages of other nodes.

A. *Simulation Parameters*

The simulation parameters which have been considered in this work are given in Table I below.

TABLE I. Parameters used in the simulation.

Parameter	**Symbol**	**Value**
Simulation area	-	200m×200m
Simulation time	-	5000 (time unit)
Number of agents	N	100
Zone of repulsion	ZoR	1 m
Zone of orientation	ZoO	10 m
Zone of attraction	ZoA	50 m
Initial velocity of nodes	v_0	1 (m/s)
Transmission range	R	120 m
Attenuation threshold	β	4
Time step	dt	1 (time unit)
Noise	η	[0,2]
Initial energy	E_0	0.5 J
Electronics energy	E_{ele}	50 nJ/bit
Amplifier energy	ϵ_{amp}	10 pJ/bit/m^2
Number of bits per packet	k	4000
Generation interval of sensed data	G_{int}	100 (time unit)
Sensing probability of an event	p_s	0.5

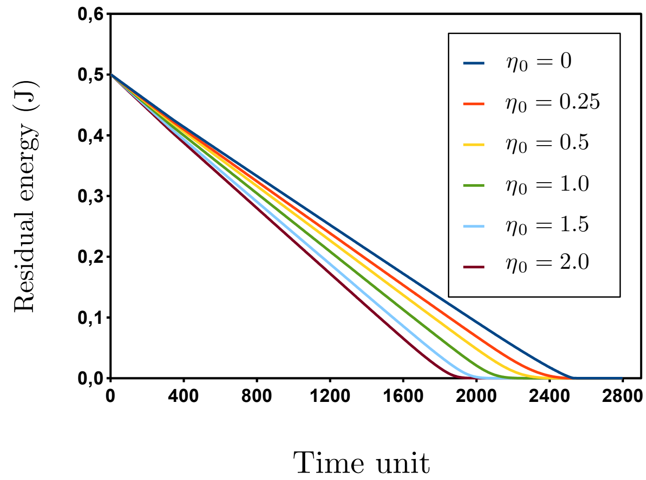

Fig. 4. Effect of increasing noise η on the Residual energy.

IV. Simulation results

In this section, we evaluate the performance of wireless sensor network under varying values of a random angle η that causes perturbations of the collective motion of agents, and therefore impacts behavioral rules of agents (e.g., repulsion, alignment and attraction) increasingly, according to the increase in value of η. Then, we analyse the impact of η on the efficiency of sensor network in terms of energy consumption, number of sensor nodes still alive, average normalised velocity, packet delivery ratio, end-to-end delay and the number of hops. The simulations are performed based on our C++ simulator and the results are averaged over 1200 replications of the simulation. Wireless communications are initiated up to $t \geq 1000$ for allowing agents to make enough interactions using the considered flock mobility model above.

To quantify the reliability aspects and features of sensor nodes dynamics in the simulation area while varying the value of η, Fig. 5(b) shows the variation of normalized average velocity under different values of η as a function of time. It is observed that the average normalized velocity decreases significantly as the value of η increases leading to a segmentation of the group of sensors info different clusters. The increase in the value of η impacts the group direction of motion, causing a high uncertainty in the movement direction of each agent, and therefore the failure of collective motion (see Fig. 3).

In addition, Fig. 4 and Fig. 5(a) show that both the residual energy and the number of sensor nodes still alive decreases significantly as the value of η increases. This can be explained by the fact that the increase in the value of η may cause an elongation in the scale of the sensor network, and therefore the number of interferer senders may decreases significantly as each sender will have a limited number of neighbor senders in its local neighborhood, and therefore the throughput of communications may increase significantly. This means that the number of senders authorised to send data at the same time unit will increase as they sense that the channel is idle (see Fig. 2). The increase in the rate of sending may result

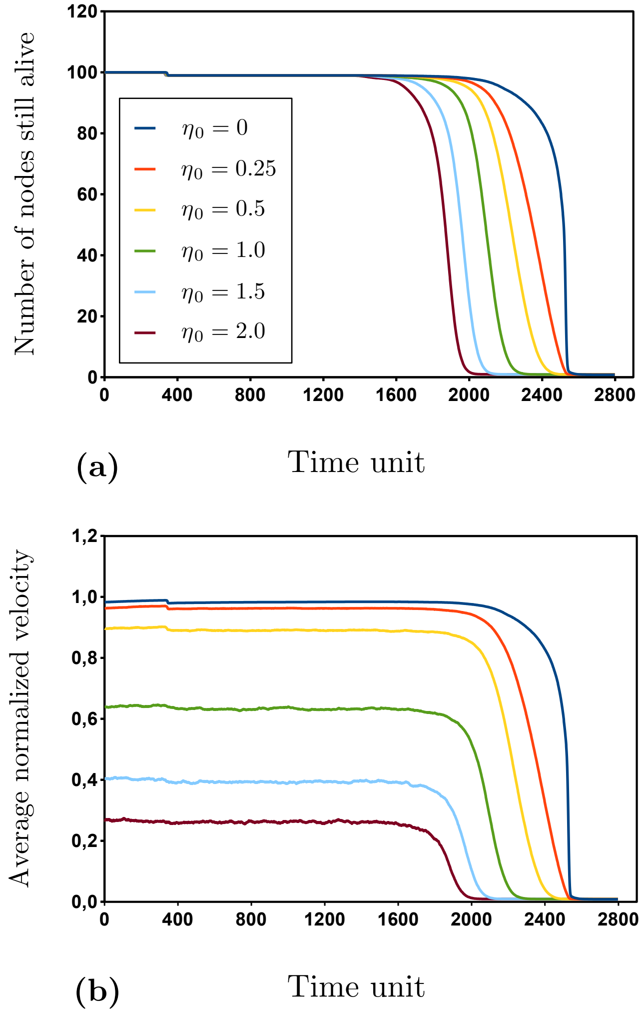

Fig. 5. Effect of increasing noise η: (a) Number of sensor nodes still alive and (b) Average normalized velocity.

in a supplementary consumption of energy and a decrease in the number of sensor nodes still alive as a function of time. Moreover, Fig. 5(a-b) shows that there is a correlation between the average normalized velocity and the number of sensor nodes still alive. We can explain that by the fact that the decrease in the sensor nodes still alive is related mainly to the group size and the spatial distribution of sensor nodes between each others in the network area.

Fig. 6 and Fig. 7 show that the packet delivery ratio and the end-to-end delay decrease significantly while η is increasing. This may be explained by the fact that a considerable proportion of packets are not able to reach the destination due to the appearance of clustering and an absence of relay nodes between the sender' cluster and the destination cluster, especially when η reaches a high level. The decrease in the end-to-end delay explains that the channel is not constrained by a congested state as each agent does not have many neighbors in its neighborhood because of the clustering phenomenon. Moreover when $\eta = 0$, all packets are received from nodes that

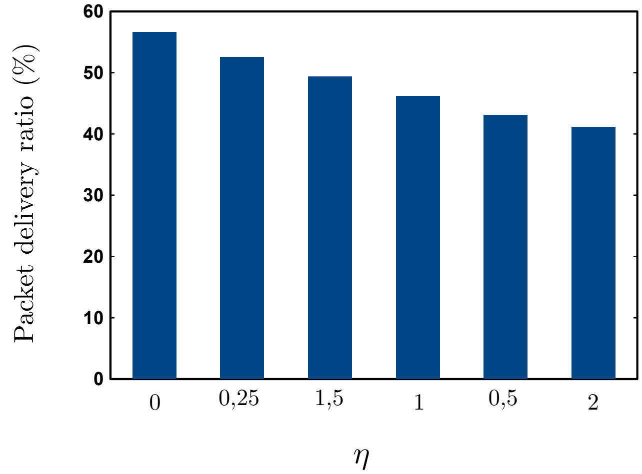

Fig. 6. Effect of increasing noise η on the packet delivery ratio.

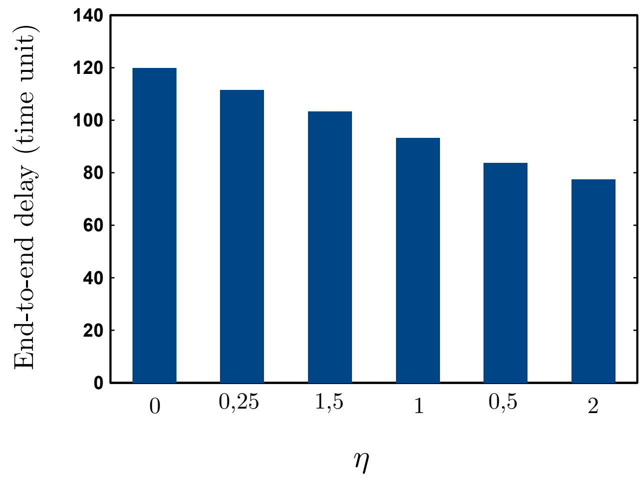

Fig. 7. Effect of increasing noise η on the end-to-end delay.

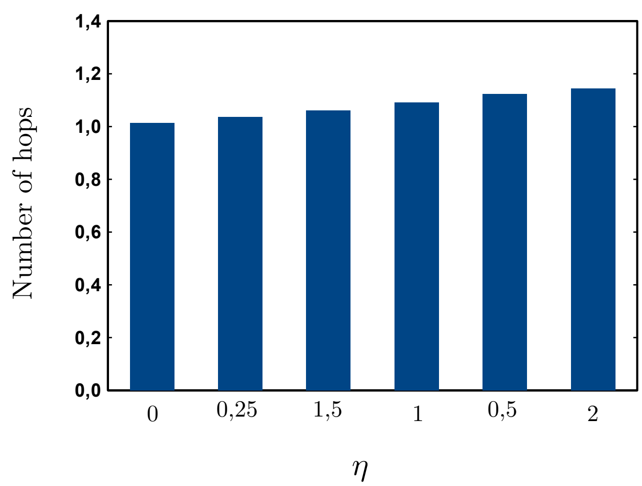

Fig. 8. Effect of increasing noise η on the number of hops.

are one-hop away (see Fig. 8). In the contrast, when $\eta > 0$, the number of hops is increased slightly as a proportion of packets are received from senders that are more than one-hop away due to an elongation in the group and clustering. This situation means that some data packets need relay nodes so as to reach the destination node.

V. Conclusion

In this paper, we have provided a detailed analysis of a mobile sensor network based on a flocking mobility model to ensure the coherence in collective motion of agents in the simulation area. The mobility of nodes is provided via a set of simple rules that govern the interaction between nodes in the three non-overlapping behavioral zones. We analysed and studied the impact of varying the noise level on the efficiency of the wireless sensor network in terms of energy consumption, number of sensor nodes still alive, average normalized velocity, packet delivery ratio, end-to-end delay and the average number of hops. Our results show that the dynamics of the agents group and the sensor network are both affected significantly with varying the noise. We observed that an increase of noise provokes not only a significant decrease in the sensor network lifetime, but also a reduction of the reachability due to a segmentation of the network into small clusters of alive nodes. Future work will focus mainly on the impact of obstacles on the sensor network formed by the agents group. Accordingly, agents behavioral rules will be extended to support obstacles avoiding. The main challenge will reside in the fact that the sensor network topology is expected to encounter a supplementary perturbation, and therefore a significant increase in the data loss and end-to-end delay is expected to result when some nodes are unreached within the sensor network.

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