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MAC Protocol for Data Gathering in Wireless Sensor Networks with the Aid of Unmanned Aerial Vehicles

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***Abstract*—Data gathering in wireless sensor networks by employing unmanned aerial vehicles has been a subject of real interest in the recent years. While drones are seen as an efficient method of data gathering in almost any environment, wireless sensor networks are the key elements for generating data because they have low dimensions, improved flexibility, decreased power consumption and costs. This paper addresses the communication at the Medium Access Control (MAC) layer between static deployed sensors and a moving drone whose unique role is to collect data from all sensors on its path. The most important part of the proposed protocol consists of prioritizing the sensors in such a manner that each of them has a fair chance to communicate with the drone. Simulations are performed in NS-2 and results demonstrate the capabilities of the proposed protocol.**

***Index Terms*—data acquisition, wireless sensor networks, unmanned aerial vehicles, wireless application protocol, algorithm.**

I. Introduction

Wireless sensor networks represent a research field that still did not reach maturity. It has a lot to demonstrate and to prove in the near future. Wireless Sensor Networks (WSNs) have a lot of potential and a variety of domains can incorporate and use this technology [1-4]. The prediction is that in the next 10-20 years we will have wireless sensors in every home and in most of our electronic devices.

As simple and low-cost as they seem today, as complex and efficient they are when we study them in depth. The main interest when talking about wireless sensor networks is linked to the power consumption constraints for the sensors. They are mobile and use batteries or different forms of energy harvesting [5-7]. Depending on the environment in which they function, they can use different forms of energy storage or generation. For example, some sensors may use solar regeneration techniques to replenish their energy sources. Others may use different environmental factors into their advantage for the purpose of long-term autonomy.

Another important aspect is the mobility factor [8-10]. Nowadays, all technologies have been developed to be as portable and mobile as possible. Manufacturers developed equipment to aid consumers and satisfy their needs imposed by the necessity to constantly be in motion. To address the mobility factor of Wireless Sensor Networks, Unmanned Aerial Vehicles (UAVs) are seen as the best solution for sensor transportation, data gathering, surveillance, etc., because they are not bound to any physical factors like other approaches (e.g. ground access, speed), being able to enter environments that otherwise seem impossible to access.

Data gathering in wireless sensor networks with the aid of an unmanned aerial vehicle can be a challenging task in some environments where the node density is high and where the process of data collection can be hardened by the high probability of collisions. To lower this factor and to assure that every node has the possibility to communicate with the drone, we have proposed the use of a prioritization mechanism to control the order in which sensors send their data to the collecting drone. The prioritization becomes an important part of the data gathering because, depending on how it is made, the protocol works efficiently or not. Thus, we searched for a solution that would offer each sensor a fair chance to send its data. A node that is closer to the drone would have a higher priority than a node that is at a greater distance and has a larger window of communication with the UAV.

To prove the performance of the proposed MAC protocol, NS-2 simulations were made. The results show that it achieves a significant improvement when compared with similar protocols.

The remaining of the paper is organized as follows. Related work is presented in Section II, the proposed MAC protocol is detailed in Section III, simulation results are revealed in Section IV, and, finally, conclusions are drawn in Section V.

II. Related Work

In this section, we are going to present relevant work on using UAVs for data gathering.

In [11] the authors introduce a method that organizes sensors into clusters and plans the trajectory of the drone in such a manner that it may communicate with each cluster once, get the data and then move to the next one, without consuming extra energy or time. In [12], a more complex solution is presented. A certain number of UAVs are splitting the area of sensors in an equal manner, based on the remaining battery and distance to be covered.

An alternate method is described in [13]. It uses adaptive contention window strategy in order to alleviate congestion in wireless sensor networks. Another point of view is presented in [14], by using circular shift routing in inter-region with the goal of obtaining balanced energy consumption among cluster heads. A special case is detailed in [15], where a particular class of wireless sensor networks is used in form of a strip-type topology.

The authors of [16] present a classification of existing MAC protocols and a comparison between them. Moreover,

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the paper reveals details, advantages and disadvantages for each protocol.

The proposed solution in [17] for minimizing the packet loss was to organize the time for channel access in consecutive time frames, while each time frame is composed of one or more timeslots. The size of a timeslot varies and must be enough for a sensor to transmit its data and receive acknowledgements. So basically, each node will randomly select a timeslot and ask the permission of the drone for it. If it gets a positive response, the node stops requesting timeslots and waits for its turn. The response contains the exact time when the node has connectivity to the drone. The UAV will start the communication process after all sensors are allocated a certain timeslot. An interesting approach is presented in [18] where the authors focus on resource allocation for data gathering.

III. Proposed MAC Protocol

The proposed MAC protocol is based on the 802.11 standard. Many modifications have been made to the original version, from removing the RTS/CTS mechanism, to modifying the data transmission phase completely.

The decision to work with Wi-Fi (802.11) was taken after comparing it with Personal Area Network (PAN) technologies (802.15) and WiMAX (802.16). When compared with Bluetooth (802.15.1) and ZigBee (802.15.4), Wi-Fi is the best choice, as it has higher data transmission speed (twice the speed of Bluetooth and three times that of ZigBee), a larger transmission range, a much lower complexity of the MAC layer (five times lower than Bluetooth and slightly lower than ZigBee), and the best normalized energy consumption (mJ/Mb) ([19, 20]). When compared to using UWB for PAN, its data speed is lower, but the small range assured by UWB disqualifies it for the use in our scenarios. Regarding WiMAX, in 802.11, the devices can communicate without an access point being present, while in WiMAX the presence is mandatory. This is a constraint, which drastically limits the areas in which it can be used, and increases the costs.

The already defined 802.11e prioritization mechanism does not help in drone-sensor communication because it does not take into account the mobility factor. So, a proper prioritization cannot be deployed. The prioritization needs to be related to the trajectory of the drone and not to the quantity of messages that a sensor has to transmit. In this manner all nodes would have a fair chance to send data.

We created our own collision avoidance mechanism by controlling the activity of every sensor with a very well planned prioritization mechanism, as we are going to detail further in this section. Furthermore, the data transmission mechanism will permit sensors to transmit data only when a drone is in their presence, otherwise they remain idle. In this manner, no energy is wasted and no packets are dropped or lost. In a classic 802.11 scenario, if the receiver is not in the range of the transmitter, the packets are dropped and energy is consumed useless. In this manner, the proposed protocol is energy efficient and data is gathered with minimum loss.

A. Frame presentation

The BEAM frame is periodically sent by the UAV in order to announce its presence and to activate all the sensors in its vicinity. By default, all sensors are in idle mode in order to preserve the energy and reduce the power consumption. Moreover, this frame is used to start the prioritization phase and contains the GPS coordinates of the starting point, current location and ending point of the UAV. It is assumed that the UAV has a linear trajectory. All this information is going to be used by each sensor, along with its own coordinates, to calculate the priority as we are going to present in more detail later in this section.

The PRIORITY (PRI) frame is used to announce the drone that the sending sensor has the highest priority and will start sending as soon as the UAV will signal it to start. This frame contains a field in which is stored the amount of data packets that the sensor is planning to send to the drone. Thus, the drone knows exactly the amount and will efficiently manage the transmission phase by reducing the time it waits to see if there are more packets to be received.

The BUSY frame is sent by the drone in the moment when it receives a PRI frame. It has the role to announce all other sensors that the UAV will get busy with the sensor that initiated the PRI frame and cancel their timers for sending the PRI frame. Furthermore, the originating sensor will start sending its data in the moment when it receives this frame. We used this frame in order to prevent the hidden node issue, which is a common problem that arises in wireless environments. A hidden node is a node that is not in the range of the source that is transmitting a frame but is in the range of the destination of that frame. So while source node A transmits to the destination B, the node C senses the channel idle so it may try to also send a frame to node B. Doing this, at node B appears a collision and the frames are dropped. So, nodes A and C are considered to be hidden to each other. With the BUSY frame, every surrounding sensor will know that the drone is busy, reschedule their timers and collisions are avoided.

The CLEAR frame is sent by the UAV in the moment when it receives the amount of packets that was initially advertised in the PRI frame. It has the role to announce all the sensors that are in the neighborhood of the drone that the communication ended and they can start the prioritization phase once again. This frame has a similar format with the BEAM frame because it restarts the prioritization phase for the remaining sensors.

B. Communication process

The entire communication process of the protocol can be summarized into a single activity diagram that is presented in Figure 1. The first decision is based on the PRI timer. If this was previously set, the second step is to check if it has expired and if it has, a PRI frame is generated and sent in order to gain priority for data transmission. If it hasn`t yet expired, the sensor returns to idle mode.

In case the PRI timer hasn`t been previously set, the sensor checks if a BEAM or CLEAR frame was received. These indicate that the drone is in the area and the prioritization phase can start. The formats of the frames are similar, but one is sent periodically to advertise the presence of the drone (BEAM frame), while the other is sent when the transmission between the drone and a sensor is over and the cycle may restart (CLEAR frame). If one of the two is received and the sensor has data to send, it schedules a PRI

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timer based on its position. If it has no data to send, it returns back to idle mode.

If a PRI frame is received by the drone, it schedules a BUSY timer. After the expiration, it generates and sends the BUSY frame to all sensors, announcing that it is going to communicate with the node that originated the PRI frame.

In case the sensor receives a BUSY frame, it verifies the priority address field to see if it is the one with whom the drone will start the communication. If it is not a match, it reschedules the PRI timer and returns to idle mode, waiting for the designated node to finish the data transfer. If the address matches with the MAC of the sensor, it starts sending data.

While the drone receives data packets, it sends acknowledgements and checks if the number of packets that was advertised in the initial PRI frame has been reached. In that case, the drone schedules a CLEAR timer. After its expiration, it generates and sends the CLEAR frame to announce all sensors in its area that it is free and can start competing again for priority, based on their position. In case the number of packets was not reached, it waits for the communication to finish.

The last part of a protocol run consists of receiving an ACK frame by a sensor. In this case, the node has to see if it still has data to send and, if it does, the sensor continues doing so. Otherwise, the communication ends.

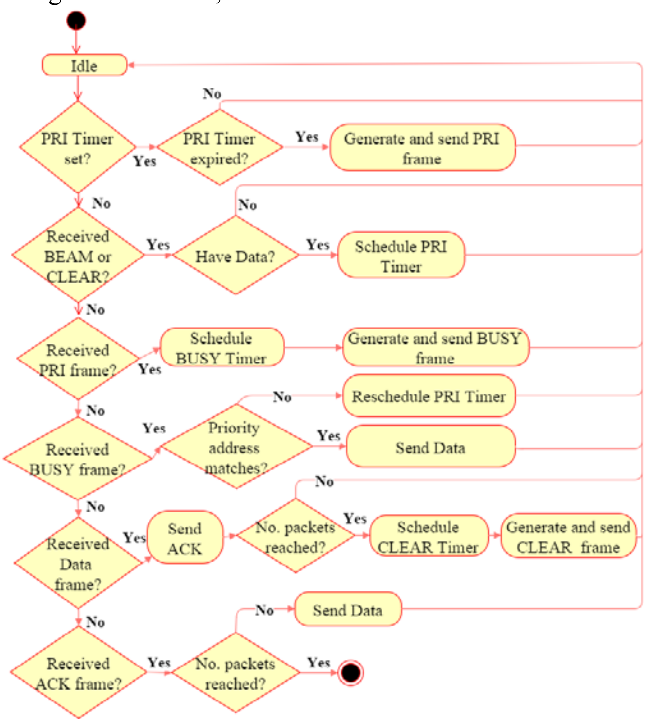

Figure 1. Activity diagram for protocol run

C. Operating mechanism

The operating mechanism consists of three main phases: initialization, prioritization and transmission.

In the first phase, the drone uses BEAM frames to advertise its presence. In order to preserve the energy, all sensors were set in idle mode. They will get activated only in the moment when the UAV is in their vicinity. Beyond this action, an intermediary step is established, before the transmission part, where a prioritization is made in order to avoid collisions.

The BEAM frame has a crucial role in the proposed protocol. Its information is used in the second phase and is very important for the prioritization mechanism. The frame contains a field named "Movement coordinates" in which multiple coordinates are encapsulated. The start and stop points are stored in this field to help each sensor calculate the trajectory of the moving UAV. Furthermore, it contains the coordinates of the drone when it generated the BEAM frame. It is important for the sensors to estimate the position of the drone on the trajectory and to use it when comparing with their own, in order to see which are more prior to send data. Without all of these, the prioritization cannot be made.

After receiving the BEAM frame, the initialization phase ends when the sensor moves from idle to active mode and the prioritization step starts. At this point, every node will use the received information to establish an order in which they can send data with a minimum chance of collision. They use the coordinates from the received frame to find the position of the drone on the trajectory. First, they are going to use some simple geometry to calculate the coordinates of a point on a line, as one can see from the equations (1) and (2):

$$x_P = \frac{1}{k+1} x_{Start} + \frac{k}{k+1} x_{Stop} \tag{1}$$

$$y_P = \frac{1}{k+1} y_{Start} + \frac{k}{k+1} y_{Stop} \tag{2}$$

where x_p and y_p represent the coordinates of the point where the drone was on the trajectory when it generated the BEAM frame, while k represents a proportionality constant between the two segments created on the trajectory (e.g. $X_{Strart}X_p$, X_pX_{Stop} or $Y_{Start}Y_p$, Y_pY_{Stop}). This position is needed for the comparison with the position of the sensor, for the purpose of seeing which one has the smallest window of communication.

To better explain the concept, we are going to exemplify by the concrete scenario presented in Figure 2: 3 static sensors and a moving drone. The coordinates of the sensors are: x_1 and y_1 for sensor 1, x_2 and y_2 for sensor 2 and for sensor 3, x_2 and y_3. One can observe that sensors 2 and 3 have the same coordinate on the X axis. The one with the higher value on the Y axis has a greater priority. Sensor 2 has a smaller period of time than sensor 3, to communicate with the drone, because dx_2 is smaller than dx_3, as can be seen from the figure.

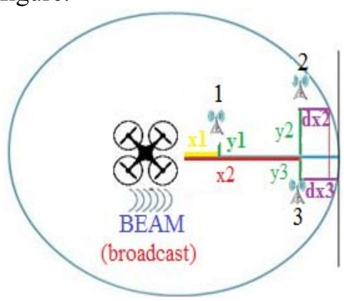

Figure 2. Distance measurements

The selection and prioritization mechanisms include a timer that is set by each sensor. This timer is calculated as in the following equation:

$$\text{PRItimer} = [(\text{dx} + 400) - 0.2 * \text{dy}] * 0.00005 \tag{3}$$

where dx represents the difference in meters on the X axis between the position of the drone when it generated the

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BEAM frame and the position of the sensor, while dy is the difference in meters on the Y axis between the position of the sensor and the position of the drone on its trajectory, when it is in the same coordinate on the X axis. It is assumed that the flying altitude of the drone is relatively constant for a large area. Dx and dy help to create a timer that will generate a PRI frame at expiration. 400 is a constant that represents the transmission range of the sensors. It helps to differentiate between sensors that are in front of the UAV with lower priority from the ones behind the UAV with higher priority. The other two numeric values are generated using heuristic technique of trial and error. We use 0.2 for the Y axis to differentiate static sensors that are at the same X value, but at various Y values, while the drone is flying on the X axis. The 0.0005 value is used in order to reduce the value of the timer to not waste time in the simulation, but to give sufficient time for all receiving sensors in the range of the UAV to process the BEAM/CLEAR frames. The sensor with the smallest timer will be the first one that will generate a PRI frame and send its data as we will see later on. This frame contains a field named "Number of packets" in which the sensor stores the precise quantity that it has to send to the drone. This is relevant because the UAV will thus be able to compute the exact period of communication. As a result, the communication is more precise and no extra time is wasted like in the case of the traditional standard 802.11.

When the drone receives the PRI frame from the sensor, it will generate, as a response, a BUSY frame. The UAV will store in the "Priority address" field, the value of the sensor that originated the PRI frame. When the drone broadcasts this frame, all receiving sensors, except the one that matches the value in the "Priority address" field, will delay their PRI timers with a certain value. In the same time, the selected node will start sending its data. With this method, the possibility of the hidden node problem to appear is excluded. This issue can cause a lot of collisions and loss in the network if it is not taken into account. If the drone issues the BUSY frame, all surrounding sensors will modify their timers. If a sensor would broadcast such a frame, only its neighbors would delay their timers, while the other sensors that are in the vicinity of the drone and not in the one of the sending sensor, will not modify their timers and collisions would occur. This is the mechanism implemented by our proposed protocol for lowering the probability of collisions. By reducing the collisions we save time and, more important, energy.

When the selected node receives the BUSY frame it triggers the third and last phase, transmission. The sensor starts sending its packets because it has priority and knows that all other sensors are waiting for it to finish before they can start the prioritization step all over again. While each packet is received, the drone issues an acknowledgement frame and increases a counter. When this counter reaches the value that was initially advertised in the PRI frame, the UAV knows that the communication has finished and it can announce the remaining sensors that they can restart the competition. The drone broadcasts a CLEAR frame to announce everybody that the communication process with the selected sensor ended. The format of this frame is similar with the one of the BEAM frame and it has the same role: to create the prerequisites for the prioritization phase. This last frame can be included in the transmission because it marks the end of this phase. In the same time, it can be included in the initialization phase because it signals all remaining sensors to restart the competition, by acting as a BEAM frame.

Even though we have introduced four types of frames, they help the protocol to be efficient in terms of success rate and collision avoidance. Every step is well documented and all actions are trigger-based, as a reaction to a previous step. Nothing is left at random.

IV. SIMULATION RESULTS

The proposed protocol was tested by using the Network Simulator 2, version 2.34. We used the two-ray ground reflection model and an omnidirectional antenna for each node present in the simulation. We used these settings because we wanted to have similar configurations with protocols developed by other research teams. By maintaining these settings, we can make a comparison between protocols and draw conclusions based on the results.

Table II summarizes all the settings of the simulations.

TABLE I. SIMULATION SETTINGS

Configuration	
Carrier sensing range	400 meters
Distribution area	2500 meters x 2500 meters
Sensors	static
Unmanned Aerial Vehicle	mobile
Unmanned Aerial Vehicle speed	50 meters/second
Distributed Coordination Function Interframe Space	10 milliseconds
Short Interframe Space	5 milliseconds
Slot size	1 milliseconds
Maximum queue length	10 packets
Packet size	100 bytes
Packet generation	Constant Bit Rate

The first simulated scenario (illustrated in Figure 3) consisted of 13 static sensors, deployed in strategic positions, and a drone that is moving from left to right. This scenario was used to evaluate the capabilities of the protocol under certain conditions. The blue line represents the trajectory of the mobile UAV. In green are depicted the coordinates of each node present in the simulation.

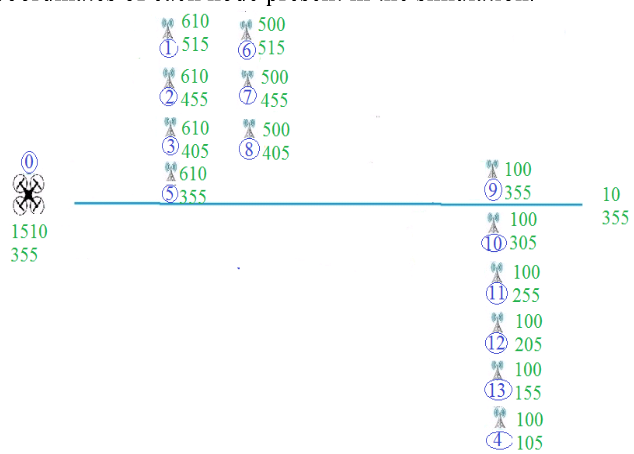

Figure 3. Scenario for simulation

The simulation indicated that the protocol behaves as expected. The nodes are selected in order, the one with the

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shortest communication window is first and the one with the largest comes last, as explained in the previous section. The order in which the sensors communicate with the flying drone is: 1, 2, 3, 5, 6, 7, 8, 4, 13, 12, 11, 10 and 9.

Different runs were performed in which the quantity of packets sent was varied (5, 10, 15, 20 data packets/sensor) and all were a success. No collision occurred and the success rate was 100%.

In another simulation the speed of the drone was modified to 75 meters/second. And, as expected, the success rate remained unchanged.

Furthermore, several simulations were conducted in order to compare our proposition with similar protocols. The scenarios consist of one drone that will act as a collector and multiple sensors placed at various locations. Our protocol was compared with two other similar protocols: one which randomly selects sensors and schedules them to a specific timeslot (as presented in [17]) and one in which prioritization is made based on the shortest distance (a derivation of the proposed protocol).

For the first comparison, the goal was to observe the success rate of data packets when the amount for each sensor is modified. A higher amount of data packets for each sensor translates in more traffic in the network and in a higher possibility of collision. We can see from this scenario how each protocol reacts to different loads in the network. The scenario includes 13 sensors and a drone, with the settings presented in Table II.

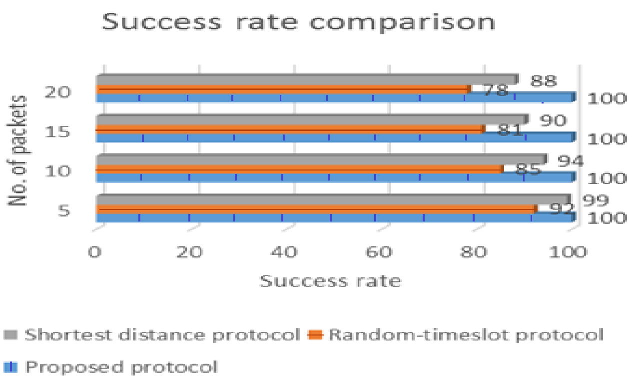

Figure 4. Success rate comparison chart

Figure 4 presents the success rate chart in which all three protocols are compared. In all four cases, our protocol had a success rate of 100%. The most inefficient of the three protocols is the random based one. Basically, each sensor asks for a timeslot, the drone randomly allocates one to the requesting sensor and replies with the specific timeslot. In this manner, the sensor knows when it has the window to communicate with the drone. The advantage of this protocol is that it induces very low delay into the network and the load is also minimum. But the performance is mediocre and not suited for applications in which reliable packet delivery is mandatory. In applications where packets can be lost and reliability is not mandatory, this type of protocol is more suitable. If for 5 packet-load/sensor the success rate on the simulation is acceptable (92%), at 20 packet-load/sensor the success rate drops to 78%.

On the other hand, the protocol that is based on the shortest distance is not a bad choice in some scenarios, because it can be efficient if the number of sensors is limited and if they are placed at different locations on the X-Y axis. It has a similar mechanism with the one that we proposed, but in some specific scenarios (Figure 3), it has a lot of problems and the prioritization is not made accordingly because the closest sensor is not the one with the greatest priority (it can be closer, but the window of communication with the drone can be larger when comparing with its neighbors, which indicates a problem in the selection). Some nodes may lose the opportunity to send their data because of the bad prioritization. As can be seen from the chart, at 5 packet-load/sensor the success rate is almost perfect and is decreasing slowly to 94 and 90 while the number of packets that each sensor sends increases. The lowest rate is at 20 packet-load/sensor (88%). For some applications it may still seem as a good solution. But if one makes a comparison, it is not as good as our proposed protocol because it has a lower success rate even if the load of the network is almost similar. Also, it is a little better than the random based one, but it increases the load of the network a lot more than the random one.

The second scenario for comparison targeted the number of retries per transmission at different speeds. The speed at which the drone flies over the sensors to collect data was varied from 25 to 50, 75 and lastly 100 meters/second. A fixed number of packets, that each sensor had to send to the drone, was used: 5 packets/sensors. The reason was to avoid having a heavy-load on the network because this was not the purpose of this simulation. The end goal was to observe the impact of speed over the quality of transmission. The scenario remains similar with the one used in the previous comparison.

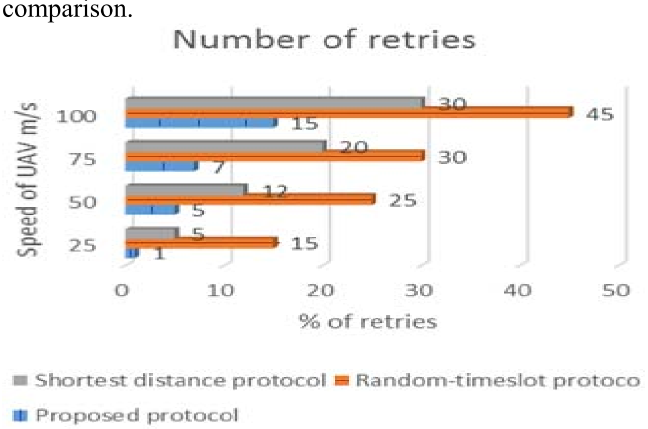

Figure 5. Transmission quality comparison chart

From Figure 5 one can conclude that, as expected, the random based protocol is the one that has the highest rates of retries for all scenarios that we tested. The results back up our theory in which this protocol is not efficient in terms of reliability and success rate. Furthermore, it is not energy efficient either, because every retransmission consumes extra energy and this may not be convenient for some applications. As one can see from the chart, when the speed increases, so does the percentage of retries. This action is normal because the wireless medium is susceptible to noise, errors and collisions. When the speed increases, the window of communication between the UAV and the sensor becomes smaller. If at 25 m/s it has 15% retries of the total packets exchanged, at 100 m/s it has an overwhelming value of 45%. One out of two packets is resent every single time. For time and energy efficient applications this protocol is a

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total failure for this configuration. In exchange, the shortest distance prioritization protocol has decent values in terms of retries. If at 25 m/s it has only a 5% chance to retry, at 50 m/s it reaches a value of 12%, while at 100 m/s the value increased to 30%. These results are decent, but there is always room for better, as we can see from our proposed protocol. It has only 1% chance to retry at 25 m/s, 5% at 50 m/s, 7% at 75 m/s and only 15% at 100 m/s. These are very good values in comparison with the previous two protocols.

We can conclude from the obtained results that our protocol has reached its designed goals and is a good solution for applications that require reliability and energy efficiency.

V. Conclusion

Data gathering in wireless sensor networks can be a difficult task in some scenarios. Many factors can influence the results, from environmental to technical issues. UAVs have been seen as the revolutionary solution for data gathering because they can break many physical limitations by doing all the activity while flying around equipment. Most problems were generated by terrain factors or limited access to certain areas, but with this solution most problems are solved.

Drones are seen as key equipment, meant to replace the physical factor from some equations or to simply ease the access to some areas. The drawback stands in the limited energy capacity. Some run on batteries, others have alternative methods for energy generation. This is why energy efficient protocols for data gathering have been one of the most researched topics at different conferences. Our proposed protocol comes to address this issue and demonstrated its capabilities through the simulations that were ran in NS-2. The advantages include reliability and a high success rate, energy efficiency, while the downside consists in a higher load in the network generated by the control frames used by the protocol.

When compared to similar protocols, we have proven with the help of simulations that our proposition has improved capabilities and can be seen as a good solution for a future implementation.

The proposed protocol deals with the most important problems identified in drone-sensor communications. The prioritization mechanism guarantees that the drone is able to collect data from networks with high densities and limits the number of retransmitted packets when the speed of the drone increases. The initialization mechanism enables sensors to transmit only in the presence of a drone, limiting useless power consumption. The BEAM and CLEAR frames help the protocol to be efficient in terms of time, every millisecond being counted for.

As future work we intend to study the power consumption and the overhead induced by the proposed protocol and compare the results with those of other similar data gathering protocols.

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