Scheduling Mechanism for Energy-Efficient Communication in Hybrid Wireless Sensor Networks

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Abstract: The paper discusses a topic at the frontier of two domains that are subjects for intensive research in recent years, namely the Wireless Sensor Networks (WSNs) and Unmanned Aerial Vehicles (UAVs). One of the main issues addressed in WSN is energy consumption and communication has the principal responsibility. Scheduling schemes for alternating active with sleep periods for nodes represents the most effective approach. This work considers the scheduling mechanism when the gateway node of the WSN is performed by an UAV, thus the topology is not fix. Additionally, the authors propose the use of directional antenna for improving the efficiency of the communication. In this way the ground nodes communicate only with the UAV, forming a hybrid WSN. The novelty of the work consists in the proposed architecture together with the communication algorithm that can offer the intended life of several years for a WSN.

Keywords: Wireless sensor network, unmanned aerial vehicles, energy-efficient communication, sleep scheduling, directional antenna.

1. INTRODUCTION

Nowadays we are witnessing how fast the unmanned aerial vehicles (UAVs, also known as drones) are integrating in all kind of applications. First major field where the UAVs were introduced was the military applications. There were two types of so called UAV's, one referring to remote controlled pilotless aircrafts (RPA) and the other one to autonomous aircrafts. The accelerated advancement from all directions of research fields involved in designing and controlling UAVs seem to provide a bright future of UAVs integration. Some examples provided in (Castillo et al., 2005) are supervision of aerial space, urban traffic, management of natural risks (e.g. active volcanoes), of environment (measuring air pollution, supervision of forests), intervention in hostile environments (radioactive atmospheres, removal of mines without human intervention), management of ground installations (dams, lines with high tension, pipelines), agriculture (detection and treatment of infested cultivations) and aerial shooting in the production of movies. It can be observed that there are applications for which the UAVs have to acquire date from ground sensors. This is done through establishing a radio link between UAV and ground sensors. A particular and useful scenario is the situation when the ground sensors were deployed (with less control) by the UAV itself (consider the hostile environment). The ground sensors are limited in energy capacity and, therefore, the same issues that are met in wireless sensor networks (WSN) can be applied here, but with an important difference: the sink node (or gateway) is moving (flying) with severe constrains about its trajectory. The authors have seen this type of network as a hybrid wireless sensor network. The goal of this paper is to describe the communication issues between the UAV and ground nodes and provides an efficient method for prolonging the life of ground nodes which are known to be battery limited. It is also very important to see the described approach not only as applicable to a particularly scenario but to a broad class of problems that involve mobile robots that have to cooperate.

This paper considers the following scenario: a number of sensor nodes are deployed from the UAV (Fig. 1). One way of delivering the nodes will be by parachuting them from the drone with use of their physical characteristics (aerodynamics due to their conical form). The ground nodes have limited resources capacity, in terms of energy and processing capabilities. Another problem is that the ground nodes are not equipped with powerful radio communication transceivers (otherwise they would consumed inacceptable amount of energy).

After the deployment, the drone search and discover the nodes, mapping them with high precision (through radio location methods). The mapping issue is not addressed in this paper, but only the synchronization mechanism used in communication. At this point, one simple solution for the node to get its coordinates is to incorporate a GPS receiver which will be used for a short period during deployment. Additionally, inertial MEMS (like inclinometers) can help finding its orientation.

The rest of the paper is structured as follows: paragraph 2 presents how this work compares with some similar researches, then the simulation assumption used for evaluating the algorithm are presented, followed by description of the algorithm, simulation results, discussions and finally, the conclusions.

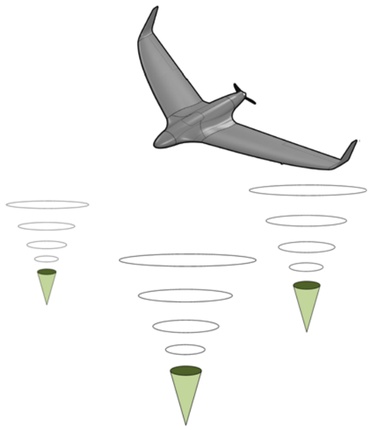

Fig. 1. Unmanned aerial vehicle (UAV) and ground sensors.

2. RELATED WORK

Both WSN and UAV are fields that attracted massive research in the past 15 years. The main focus for WSN was on communication issues (coverage, connectivity, energy consumption) and sensing. Most of the node's communication models for connectivity (k-connectivity) use omnidirectional isotropic propagation model (often bidimensional). The result is that the node will have a spherical communication coverage (a disc in 2D case). (Sujit et al., 2013) use this approach and proposed an heuristic route planning for UAV to collect data from ground sensors, arguing that an optimal solution is difficult and computational intensive. The authors decouple the problem in four sub-problems, namely determining clusters of sensors based on their communication ranges, follow by efficiently connecting the clusters, then establishing an optimized path inside the cluster and, the last sub-problem, designing the overall UAV's path. Same approach was used by (Ho et al., 2013). The above works consider the maximization of network life only through efficiently finding the gateway node within a cluster. Practically, the sensor nodes are all the time active, conserving their energy by not communicating. The present paper proposes an algorithm that deals with power states management of sensor nodes.

(Song et al., 2009) designed and deployed a sensor network for volcano monitoring. Because of the dimensions and the weight of their nodes, the deployment was done with an helicopter. The nodes' weight seems to be caused by the harsh environment and also by the type of communication, in terms of power requirement and the used of commercial off-the-shelf modules. This added the need of large batteries and large packages. The physical volume of the resulted node attracted the need of good ground stabilization. Therefore, the deployment was accurately made using the helicopter for transportation. Instead, the algorithm in this paper tries to offer a new perspective of designing such nodes in order to consume less power, thus having small dimensions, being cheap and easy to deploy large number of nodes directly from air.

(Corke et al., 2004) deployed the nodes directly from an autonomous helicopter and presents some learned lessons. The first problem was that the communication is highly dependent on relative antenna orientation. The present paper provides a solution for the above mentioned problem. Another way to deal with antenna propagation pattern was used in (Cobano et al., 2010) by flying the UAV at lower altitudes. Despite that it could be unsafely, the time spent by the UAV in the communication rage will be too small as it is shown farther in this paper. Directional antenna will provide much flexibility here and the radiated energy will be more efficiently used. The main drawback of the directional antenna is their relative orientation which is uncontrolled during deployment.

(Cheng et al., 2007) show, together with experimental validation, that what they call "load-carry-and-deliver" (LCAD) paradigm can also maximize throughput in WSN with the UAV as a data relay. Practically, instead of using a multi-hop communication between ground nodes, the UAV can overfly each node and act as relay. The main problem the authors recall is the latency. In data gathering applications which not require real time alarms, this will not be an issue. Instead, this paper tries to provide a sleeping mechanism for the nodes when they are not operating, thus to significantly increase the network lifetime.

Resource allocation in the above context is discussed also in (Zanjie et al., 2014) where the main focus is on band allocation for transmission and energy allocation for sensing and transmission. Again, it is not mentioned the synchronization mechanism that could drive the proposed algorithm. When a distributed algorithm is simulated on a PC, the synchronization is intrinsic.

On the other hand, the synchronization in WSN is widely spread research topic mainly due to its impact on energy preserving. There are deterministic and probabilistic approaches, but, as far as the authors of this paper have knowledge, they were not discussed in the context of mobile gateways as in the presented case. Hence, this is starting point for the novelty of the proposed algorithm.

3. MODELING ASSUMPTIONS

3.1 Radio coverage

First step was to endow the ground nodes with directional antennas. Thanks to their ability of concentrating radiated energy in a certain direction of interest, with similar energy as an omnidirectional antenna, they can achieve a higher level of coverage in that specific direction. This difference is illustrated in Fig. 2 where the radius of the coverage circle (omnidirectional antenna) is less than the generatrix of the coverage cone (directional antenna) when the same amount of power is used. In antenna propagation theory, the angle from the tip of the cone is often referenced as 3dB-beamwidth, being the angle between the segments in the main lobe that have a loss in power from the maximum gain of 3 dB (the power is split in half). Another strong point of directional antenna would be the diminished signal interference with nearby antennas.

The flight altitude (H) of the UAV is considered to be constant as is the tangential speed (*v*). The position of the nodes is random and can be represented on a 3D coordinates system. The antenna pattern of the UAV is wider than the antenna patterns of the nodes, thus communications is enabled once the UAV is in the node's range (Fig.2).

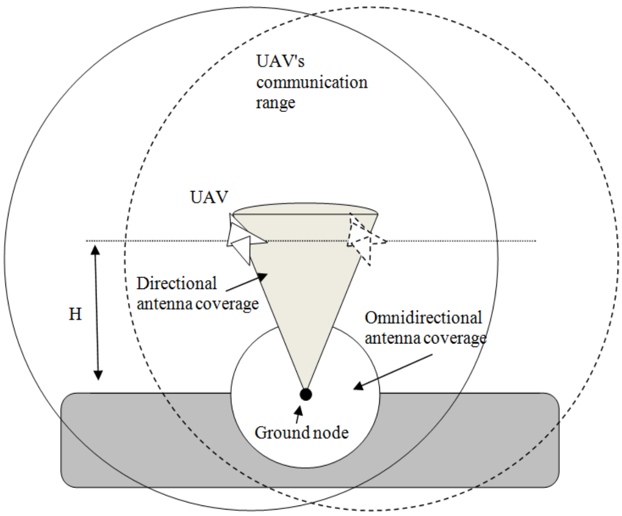

Fig. 2. Omnidirectional vs. directional antennas in the context of UAV-ground node communication link.

The intersection between the antenna pattern and the "parallel" plane at altitude H will be the node's radio coverage area (A_{RCi}) (Fig.3). The proposed approach considers that the cone doesn't necessary have its axis of symmetry (farther denoted as "steering direction") perpendicular on ground (the deployment was uncontrolled).

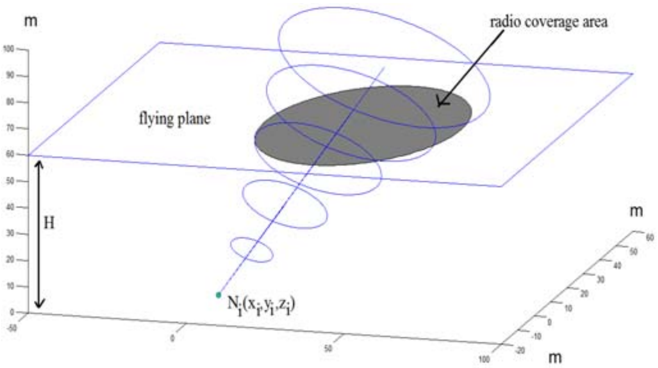

Fig. 3. The radio coverage area (conical cut) - axes are in m.

Cutting a cone with a plane raises an old and well known issue of conic sections. There are three types of conic sections: ellipse (where circle is a special scenario), parabola and hyperbola. For this simulation type, all conic sections are considered to be ellipses.

Considering the amount of data that must be interchanged, the UAV should maintain its position in the node's radio coverage for the necessary amount of time. By knowing the UAV's velocity and data interchange time interval, the optimum trajectory can be computed (Fig.4).

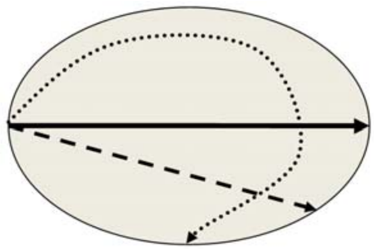

Fig. 4. Various trajectories of the UAV in the radio coverage area.

3.2 Communication and radio channel

In theory, various types of channel models exist. They can consider vegetation, multi path fading, etc. Data packet can be corrupted and channels must be able to represent that degree of influence. In the end, the following parameters that describe the corruptions at a higher level were chosen:

- *Maximum data rate (MDR)* – the capacity of the communication channel, considering the transmitter's and receiver's capabilities. Basically, this is the maximum data rate met in practice when favorable conditions exist.

- *Effective data rate (EDR)* - payload ratio per full amount of data exchanged. Some of data engaged in communication belong to the protocol overhead (headers, synchronization, error check, acknowledgments, etc.). These data is considered overhead for payload information and is subtracted, therefore EDR can be used further. EDR is computed as:

$$EDR = k_O \cdot MDR, \quad 0< k_O <1 \tag{1}$$

- *Actual data rate (ADR)* - payload ratio after corruptions and retransmissions. Not all information transmitted with EDR debit are safely received. Each corruption (including timeouts) triggers a retransmission, thus the EDR is not accurately reflecting information transfer debit. The ADR tries to introduce a safety margin for communication in the algorithm. ADR is evaluated after (2).

$$ADR = k_R \cdot EDR, \quad 0< k_R <1 \tag{2}$$

In the future, the authors intend to use MDR, kO, kR as leverages for an adaptive algorithm that will try to maximize the throughput on the radio link. At this point, experimental values for the mentioned parameters were chosen.

3.3 Energy consumption

The CPU, the transceiver along with the antenna, the sensors that include the signal adaptation chain and the battery are the elements that make together a ground node. These components can be either stand-alone or partially chip integrated (SoC). In both cases, the entire node has a power management state machine (PMSM) which can also describe the energy consumption model. In Fig.5 such a PMSM is illustrated based on a SoC from Texas Instruments (the state of the art CC2538). By comparing the energy consumption level between Active R and Sleep states (10.000:1) it can be observed the impact of a good management technique of the node's PMSM. Establishing the communication timing is a key importance factor in increasing the life expectancy of the WSN.

One of the node’s local issues is determining how long the UAV flyover must be, such that it remains in the radio coverage area and is able to transmit all the necessary data.

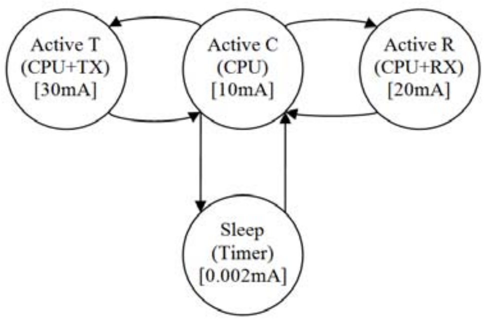

Fig. 5. Power management state machine (PMSM) of ground nodes.

4. PROPOSED ALGORITHM

Beside PMSM, each node has its own finite state machine (FMS) for this algorithm. PMSM describes the hardware state while the FMS establish how the node relates to the algorithm. The node's FMS has three possible states: just deployed, synchronized and unsynchronized (Fig. 6). First, the node starts in <just deployed> state. In this state the node configures its peripherals (timers, interrupts system, transceiver, ADCs, etc.). The entire application running on the ground node is interrupt driven (Algorithm 1).

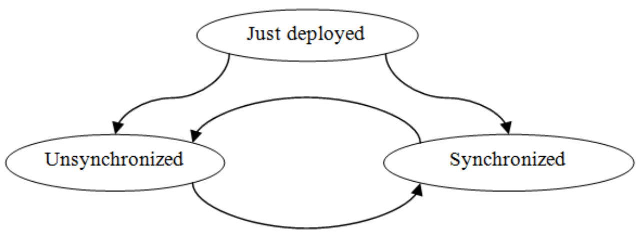

Fig. 6. Finite state machine (FSM) of ground nodes.

Algorithm 1: The main structure of the algorithm running on the ground nodes

```
CurrentNodeState=JUST_DEPLOYED;
CurrentHardwareState=ACTIVE_C;
NextSleepTime=
        ON_TIME_IN_JUST_DEPLOYED_STATE;
NextWakeUpTime=
        UNSYNCHRONIZED_WAKE_UP_TIME;
HardwareStateTimer=NextSleepTime;
//StartAcquisitionThread();
SetRFInterrupt();
StartStateTimer();
while(1){
        //infinite loop
}
```

In the <just deployed> state, the node keeps its radio in listening state for a certain period of time, waiting for a beacon signal from the UAV. If the signal isn't received, the internal timer (programmed with the period of active time) overflows and an interrupt will be issued. The algorithm servicing the timer overflow interrupt (Algorithm 2) puts the node in <unsynchronized> state. The <unsynchronized> state triggers the node to wake up from sleep at certain moments of time, remain active for a defined period while it is listening for the synchronization beacon from the UAV. This schedule is programmed on the node before its deployment, and the UAV, through its ground control station (GCS), knows about it, thus, the UAV has many "windows of opportunity" to communicate with the node.

Algorithm 2: Interrupt service for power management timer on the ground node

```
ISR(HARDWARE_TIMER_OVERFLOW){
   if (CurrentHardwareState==SLEEP){
        //woken up from sleep mode
        CurrentHardwareState=ACTIVE_C;
        if (CurrentNodeState==SYNCHRONIZED){
             NextSleepTime= ReceivedSleepTime;
             CurrentNodeState=UNSYNCHRONYZED;
        }
        else{
             NextSleepTime=
           ON_TIME_IN_UNSYNCHRONIZED_STATE;
            HardwareStateTimer= NextSleepTime;
        }
   }
   else{
         //go to sleep mode
         NextWakeUpTime=ProgrammedWakeUpTime;
         HardwareStateTimer=NextWakeUpTime;
         CurrentHardwareState=SLEEP;
```

```
            EnterSleepMode();
        }
}
```

The beacon signal can be received only during active listening (Active R) states of the PMSM. When a data frame is received in the node's receiver buffer, another interrupt is issued that is serviced by the Algorithm 3. If the node was in the <just deployed> state, the communication initiated between the UAV and the ground node uses a collision avoidance (CA) protocol because after deployment there are possible overlaps among nodes' communication areas. During this communication, the UAV receives monitoring data from the ground node and sends back the new "visiting" program. If this program is confirmed by the node and confirmation acknowledged by the UAV, the node enters in the <synchronized> state. From the <synchronized> state, the node can switch to <unsynchronized> if something goes wrong, as the communications fails issuing timeouts or the UAV is not present in communication area during the active listening period. As mentioned before, the mechanism is interrupt driven, message receiving or timer overflow being events that trigger interrupts (ISR - Interrupt Service Routines). By using this scheduling mechanism, the ground node will make best use of its energy, thus prolonging its life.

Algorithm 3: Interrupt service for data receiving on the ground node

```
ISR(RF_DATA_RECEIVED){
    switch (ParseRFIncomingData()){
        case BEACON:
            if (CurrentNodeState==JUST_DEPLOYED) {
                        AnswerWithCA();
                }
        case SYNC_MSG:
            UpdateParam();
            SendAck()
        case  SYNC_ACK:
            CurrentNodeState=SYNCHRONIZED
            HardwareStateTimer=ReceivedSleepTime;
            ...
  }
}
```

Further, after the nodes have been deployed, the UAV has the mission to scout the drop area. If a node is localized, it will receive its new timing parameters for its PMSM. By doing this the UAV will know the communication time availability interval for each node. After all of the available ground nodes have been localized and timing was established, the proposed communication algorithm can take effect. It will consist of two steps as follows:

1. Preliminary flight (PF) and

2. Data gathering flight (DGF).

In the PF stage, it is considered that each node will communicate the same amount of the data (Q_P) in the UAV overfly time interval (t_p) for the node's radio coverage area (A_{RCi}). The t_p value is given by the ration between Q_P and ADR (see 3.2). Considering v_{UAV} , the trajectory's length inside A_{RCi} can be computed as in (3).

$$L_i = v_{UAV} \cdot t_p \cdot k, \qquad (3)$$

where k>1 is a margin factor.

Q_P will contain both ways information regarding the UAV and ground node.

The node will be able to communicate the extra time needed to send the remainder of the data (Q_D) which will be collected in the next flyover. As it was presented before, the UAV will inform the node of the time of the next flyover so that the ground node can lie in a low power state with the radio elements switched off in order to conserve energy and will only wake up at the pre-established time.

During the PF the DGF trajectory is dynamically computed and timing communicated to the nodes. In DGF, the UAV will have to take into consideration the time interval established for the remainder of the data transmission, which was previously communicated by the node. The new timing for the next flight will also be computed. Alternation of preliminary flight and data gathering is also considered. If something goes wrong, the node enters in <unsynchronized> state and the UAV can synchronized it back by using the node's activity periods ("windows of opportunity").

5. SIMULATION RESULTS

The presented algorithm is deterministic and it can be easily evaluated. However, the algorithm was also tested in a proprietary developed framework for future implementation and testing. The framework is intended as tool for the integration of multiple functionalities in a hybrid WSN like the one presented here. In this way users are able to add nodes as objects with agent behavior and creating various scenarios. Each node has several proprieties among which, at this point, the interesting one are: 3D coordinates (both real and estimated), antenna orientation (the elevation and azimuth angles), transmission power level, receiver sensibility and energy left in the battery.

For this paper a simulation was conceived that considered 12 deployed nodes on a 400m x 1000m unleveled area. The nodes could fall in a not accurately controlled manner, therefore, their coordinates and orientation are arbitrary. Fig. 7 shows the nodes' deployment together with their antenna propagation patterns. It can be easily seen that there are areas where the radio coverage of nodes are intersecting. This is the reason why in the <just deployed> state the node should send data based on a collision avoidance mechanism. Further the UAV will be the scheduler in a Time Division Multiplexing (TDM) scheme for radio channel sharing. The UAV will visit each node once at 4 hours.

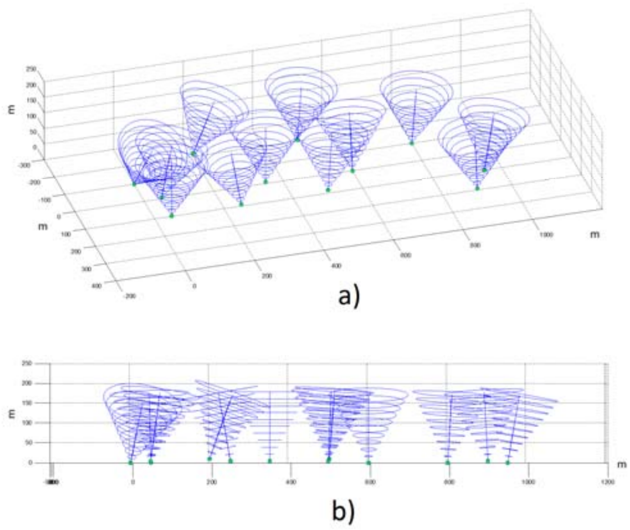

Fig. 7. Screenshot from the simulation scenario (axes are in m): a) 3D view, b)long side view.

As the title of this article specifies, the focus was not set on optimum trajectory determination but more on the synchronization mechanism and its impact on energy consumption. The PMSM energy states and application scenario were computed with real data about CC2538 from (Suyash, 2014). CC2538 is SoC from Texas Instruments that integrates in a 4x4mm chip a powerful ARM Cortex M3 microcontroller together with a ISM radio transceiver.

In this context, the parameters introduced in previous paragraphs were considered as following:

- MDR = 500kbps;
- EDR = 400kbps;
- ADR = 100kbps;
- v_{UAV} =90Km/h;
- H= 400m;
- 3dB beamwidth = 30^o=> the major axis of the ellipse resulted as a conical cut is approximately 215m;
- Q_p=100,000bytes

It can be observed that the chosen Q_p is large enough for monitoring applications. The corresponding t_p for this Qp is evaluated:

$$t_p = \frac{Q_p}{ADR} \approx 8s \quad (4)$$

From (3), the trajectory length inside node's radio coverage area is L_i=196m (for k=1.1). Therefore, it is sufficient for the UAV to fly along the major axis of the coverage area. The k parameters together with the other approximations that were made let enough room for small deviations of the UAV from established route.

The proposed algorithm was evaluated on one node against two often used methods in wireless sensor networking. One method assumes the nodes are always on active listening mode. Practically it is the most often used method (even if not directly specified) in the papers concerning WSN. Generally, all the related works that deals with communication in WSN which not discuss clocks synchronization mean they use at least always on listening mechanism. Otherwise they were unable to communicate each other in a deterministic way. The second mechanism is when the node spends only a fraction of its time in active listening mode, during when it probes the environment for messages. In case of receiving an invitation for communication it will send its data. The evaluation time for simulation was 3 days.

In Fig. 8 the always active mechanism is performed. The spikes are corresponding to the data sending periods. The gap between spikes equal 4 hours as the scenario assumes. It can be seen that the total electrical charged consumed in 3 days has been 1728mAh.

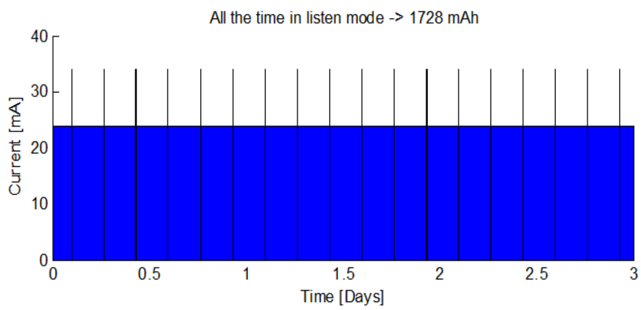

Fig. 8. Time diagram for energy consumption in always listening mechanism.

The first improvement would be to establish a ratio between time the node spends in active mode and time it spends in sleep mode. In Fig. 9 the simulation results for a ratio of 1 to 10 are presented, as the node is active for 1s on each 10 s time slot.

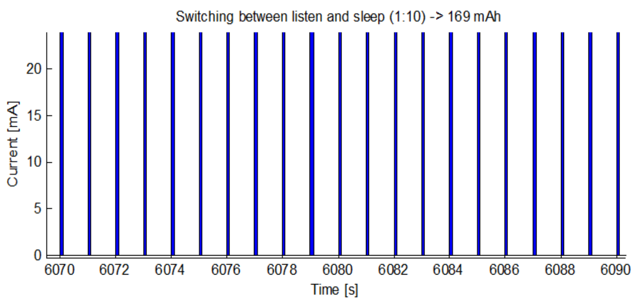

Fig. 9. Time diagram for energy consumption in 1:10 ratio listening mechanism (scaled axes).

In this case the economy is of one order of magnitude. Practically, the node would live 10 times more than in the first case. The question is how much this ratio can be diminished. The trade-off for the ratio is quite difficult as it is discussed in the following paragraph. The proposed algorithm searched to optimize this trade-off by transforming the ratio from a fix ratio to an adaptive one exactly tailored to the system needs.

Fig. 10 illustrates the proposed algorithm on the mentioned simulation scenario. Denoted by A is the initial state (just deployed) where the node waits of a longer period (30 minutes) the synchronization beacon from the UAV. Once it establish the communication it enters in <synchronized> state and the algorithm becomes deterministic as the nodes will now exactly when to wake up from sleep. B points to the state when the node is communicating with the UAV. The C region represents the period when the node becomes active in listening state for safety cases when the node became unsynchronized.

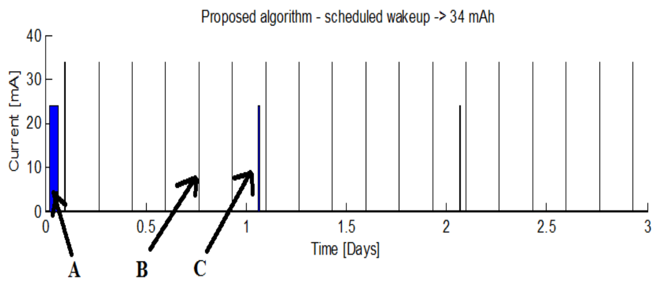

Fig. 10. Time diagram for energy consumption with proposed algorithm.

The proposed algorithm had measured 34mAh of energy charge during the 3 days time period on this particular scenario simulation. This represents 5 times less than the previous method and 50 times less than the classical one. Farther, the active period was extend with 20% as a safety margin, and the additional energy charge during 3 days was below 1mAh (Fig. 11). Practically, the active listening periods during <just deployment> state (A in Fig. 10) and the time window intended for resynchronization (C in Fig. 10) are the main energy consumption sources in this 3 days simulation.

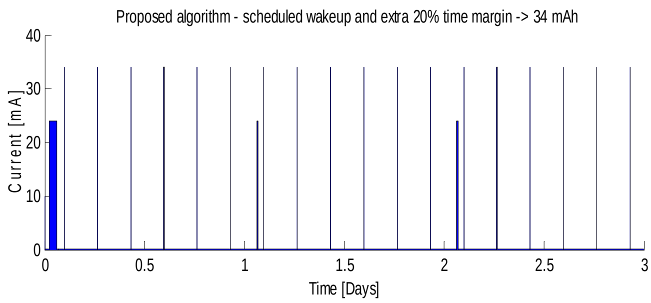

Fig. 11. Time diagram for energy consumption with proposed algorithm including a 20% safety time margin.

6. DISCUSSIONS

The evaluation of algorithms didn't take in the consideration the data acquisition from sensors. It is considered that the sampling periods together with the required energy is the same for all of the algorithms, less the case of always on listening method where the additional energy can be much lower as the node is already active. Excepting applications like seismic waves measuring, generally, the sampling frequency is small. In the case of fast processes, they most likely require also real time monitoring and alarming, therefore this solution is not suitable. In processes where only some anomalies are measured and the real time alarming is less important then this algorithm can prolong the life of ground nodes considerable. The idea of waking up nodes exactly the time needed for communication ensures the minimization of the energy consumption by the ground sensor network (WSN). The principal problem remains the clock synchronization between ground nodes and UAV. Using a GPS receiver would help on this issue but will increase considerable the energy consumption and the same applies to the node cost together with its dimensions. Experiments should be made to see exactly what is the maximum drift of the node's local clock between successive synchronizations with the UAV. At this point, for presented scenario with 4h period between synchronizations, it is clear that clock drifting is not an issue. It will become an issue if the UAV has larger time interval between patrols. This scenario can provide a lifetime for the ground nodes of several years.

The other approach of periodically waking up the node based on a particular fixed ratio has the advantage of not requiring global synchronization. The main disadvantage is the impossibility to find a better ratio than the adaptive one used in the proposed algorithm. The reasons are the risk of being asleep while the UAV is inside the node's coverage area or, if the ratio works on subdivisions of time (ex: 1ms wake and 99 ms sleeping), the switching time between power states transitions becomes not negligible. Above all this, switching between states exhibits a peak in energy consumption, as was experimentally measured in Suyash J. (2014) technical paper. Switching often, the numbers of peaks will increase, thus the energy start to increase significantly.

If various angles of elevation of steering direction are considered, along with power of the radio transmission, flying altitude and other factors, then other types of sections can be obtained. The equations used to compute the described model will permit to a ground control station to have the optimum trajectory map as simulated. Fig. 12 shows the map computed for coverage areas further used for UAV trajectory and time synchronization.

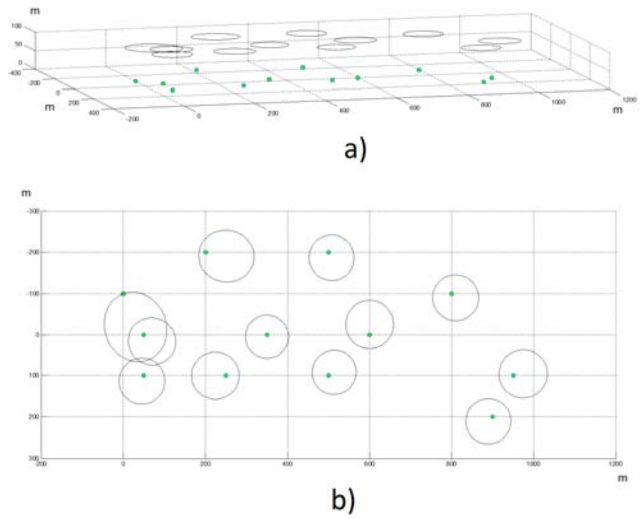

Fig. 12. The flying plane with radio coverage areas: a)3D view, b)2D view (axes are in m).

7. CONCLUSIONS

With the work in this paper the authors tried to demonstrate the utility of directional antennas and synchronization mechanism for prolonging the life of the sensor nodes from a ground deployed WSN. This approach leads to several issues that we had addressed and they are overcome by the proposed algorithm. Beside the algorithm validation, the simulation results showed a very important thing, namely that the proposed algorithm can give the intended energy autonomy for wireless sensor networks. In most of the surveys related to WSN, the nodes' life is desired to reach several years without charging. It was proved through simulation that this can be possible. Further on, the same approach can be used if the nodes are endowed with small solar panels. Practically, the main limitation will come from the chemistry of the battery.

Another important thing that should be clear emphasized is that the modeling and simulation calculus was designed to be implemented on the related ground control station (GCS) or even on the UAV. This mean that the UAV (with or without GCS's help) can compute the radio coverage map of the ground nodes after deployment. In the future, beside the practical validation of the proposed approach, the authors will focus on trajectory optimization (considering also the flying altitude and speed of the UAV) and the power level of transmission for each node (dynamically changing the radio coverage area).

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