Performance Analysis of Preemptive and Non-Preemptive Schemes in Hybrid Wireless Sensor Networks focused on the study of epilepsy

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Abstract. Epilepsy is a central nervous system disorder characterized by increased and abnormal synchronization of electrical neuronal activity and manifesting in spontaneous recurrent crisis. Then, electroencephalographic changes are presented. Different studies, such as the electroencephalogram [EEG], electrocardiogram [ECG] and electrogastrography [EGG], allow monitoring physiological signals associated to possible epileptic seizures. However, they require wired connections and therefore monitoring is restricted on factors such as limited physical movements, loss of information by disconnecting sensors and the patient needs to be in a specific area. Building on this, a system capable of wirelessly monitoring patients in mobile environments is proposed. Such system, without the above restrictions, opens up possibilities for the ubiquity study.

Specifically, this work aims at studying the performance of a Wireless Sensor Network (WSN) with Cognitive Radio capabilities for a Body Area Network (BAN) performing continuous monitoring (EEG, ECG) and event monitoring (EGG).

Keywords: Wireless Sensor Network (*WSN*), Cognitive Radio (*CR*), Body Area Network (*BANET*), Electroencephalography (*EEG*), Electrocardiography (*ECG*), Electrogastrography (*EGG*), Epilepsy.

1 Introduction

Epilepsy is a brain disorder that is characterized by an enduring predisposition to generate epileptic seizures causing neurobiological, psychological and social consequences of patients suffering this condition. This disease can be detected, according to Serratosa, by the presence of only one seizure.

Currently there is a lot of devices and tools to monitor biological signals of human beings in a wired manner for the analysis of epilepsy [1]. These signals may determine certain patterns that provide information for the prevention or control of this disease. Among the most commonly performed studies is the electroencephalogram (EEG, neurophysiological examination based on the registration of bioelectrical brain activity under different conditions), electrocardiography (EKG / ECG, representing the electrical heart activity) and electrogastrography (EGG, recording technique of gastric electrical activity). However, there is not a system that allows monitoring all these signals simultaneously and wirelessly. Therefore, in order to incorporate these features, a communication protocol for the hybrid WSN (capable of monitoring both continuous and event data) is need as well as the study of the performance of the body area network (BAN). In particular, we propose the use of a WSN with cognitive radio (CR) capabilities, where nodes can efficiently use the radio-electric spectrum to transmit event data using the continuous monitoring channels. As an additional benefit of using this technique, the lifetime of the system is increased by allowing continuos monitoring nodes to turn off their radios in order to allow event nodes to transmit their information. As such, the proposed system is also energy-efficient.

In the literature, there are papers such as [2], [3] and [4] that study WSNs with similar objectives. The reference [2] describes a wireless sensor network focused on the study of epilepsy but, the paper does not consider a cognitive ratio, [3] and [4] have a WSN including different studies of biological signals but those have a different application (to monitor athletes).

However, non of these studies propose the use of a CR system to efficiently perform the required tasks, Also, the present study evaluates the performance of the network under different environments and analyses the energy consumption and successful event probability in order to allow a practical implementation in a future work.

The WSN is based on a TDMA scheme where the first time slots are assigned to the continuous monitoring data transmission while leaving the rest of time slots available for the event-driven detections. By doing this, a collision-free system is design in such a way as eliminating any information loss.

2 System Model

First, we present the different types of bioelectrical signals that can be used for the detection of epilepsy.

2.1 Bioelectrical Signals

Cells of nerves and muscles of the human body by interaction with themselves generate bioelectric signals (also called biopotential) [5]. If the nerve or muscle cell is stimulated strong enough, above a specific threshold, then a potential action will be taken. This represents a flow of ions through the cell membrane and can be measured by non-invasive intra-corporeal methods. Examples of studies applied for these signals are detailed in *Table 1.*

Table 1. Common studies to measure biopotential signals [6].

Study	Description	Voltage	Frequency
ECG	Electrocardiogram. Representation of the heart's electrical signals.	0.5 - 4 mV	0.01 - 250 Hz
EEG	Electroencephalogram. It is the representation of the electrical signals produced by the brain.	5 - 300 μV	150 Hz DC
EGG	Electrogastrogram. It is the representation of the electrical signals produced by the stomach.	10 μV - 1 mV	1 Hz DC
EMG	Electromyogram. Representation of electrical signals from the muscles.	0.1 - 5 mV	10 KHz
ERG	Electroretinography . Representation of electrical signals from the retina.	0 - 900 μV	50 Hz DC

2.2 Bioelectric signals useful for the study of epilepsy

There are a lot of studies to measure bioelectrical signals; however not all of these signals are useful for all circumstances. Inquiring about the functionality of studies for epilepsy, different tests have been done to identify which are consistent in order to obtain patterns that infer or detect a possible seizure.

The primary study for epilepsy is the EEG, since a seizure sets in an abnormal brain activity and the EEG provides graphics depicting the brain function. Also, and based on [1], the constant study of the heart (ECG) is proposed. According to this, the system keeps a constant monitoring of signals from the brain and heart. Also, it is possible to combine studies based on gastric events. However, by adding these signals to the system, it must be considered that the gastric behavior can vary depending on the situation (ie, gastric events may be conditional on certain thresholds that the doctor or expert define). It is considered then that the EGG be included but with restrictions defined by doctor's parameters.

In conclusion, it is determined that the system will operate through the measurement of three different studies: EEG, ECG and EGG. From these signals, the system acquires continuously all information from the heart and brain while gastric electrical activity will only be considered under certain parameters that the expert determines (from this point to the end of the article, the EGG will be cited as study of *event monitoring*).

2.3 Communication Scheme

In this section, the proposed communication scheme to send both continuous monitoring and event monitoring data in the WSN is described in detail. It is considered that nodes in a Wireless Sensor Network are able to perform basic operations like sensing and communicating with other sensors, placed in a given area [7]. In this case, nodes are placed in the head of patients in order to obtain the measurements of the EEG while other nodes are placed in the patient's body to obtain the ECG and EGG signals. Also, the sink node is considered to be any wireless device (such as a smartphone or tablet) that communicates to the nodes in the network. Hence, the sink node would also be carried by the patient. As such, in this WSN, nodes are placed extremely closed to each other. The communication range among nodes is reduced. Building on this, nodes can perform direct communications and there is no need to use techniques such as clustering or multi-hop communications to relay data to the sink node.

Another important characteristic of this BANET, is that the number of nodes assigned to each biological signal is known: For the nodes that send data in a continuous monitoring fashion we have $N_c = 18$ (16 for EEG and 2 for ECG) nodes, while there are $N_e = 4$ (for EGG) nodes sending data only when a certain event occurs. For instance when the signals lay outside a certain predefined range selected by the physician. Hence, the system is formed by $N = 22$ nodes. As such, a Multiple Access Time Division (TDMA) scheme is selected. Indeed, this scheme is contention-free and nodes do not waste energy in packet collisions or overhearing like in random access protocols. Note that, in most WSNs, this cannot be done, since the number of nodes is usually not known.

2.4 Non-Preemptive Scheme

In the TDMA scheme, each node is assigned an specific time slot. Specifically, nodes resources are assigned according to Fig. 1.

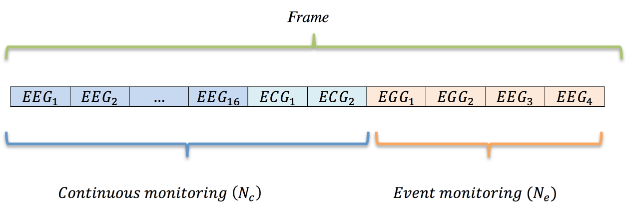

Fig. 1. TDMA-based protocol for evaluating the performance of the hybrid WSN

Note that nodes in a continuous monitoring regime, are assigned a particular time slot at the beginning of the frame while nodes in the event detection regime, are assigned a channel at the end of the frame. As such, whenever the event nodes do not transmit information to the sink node, the channels at the end of the frame would be empty. This entails an extra energy consumption since the sink node is constantly receiving the signal from all the frame and bandwidth wastage. Specially if gastric events rarely occur. However, no data is lost, since nodes (both N_e and N_c) can transmit their information in any time they have something to transmit. As such, this is an non-preemptive scheme in the sense that at no point, nodes lose the assigned channel.

2.5 Single Event Detection

In this system, we consider that only one type of event can occur in the network. As such, the system is designed in order to transmit both continuous monitoring data (EEG and ECG data) while the EGG information is transmitted in an event reporting manner, i.e., only when the electrical signal of these nodes is above or below a certain threshold set by the medical staff. The event reporting happens at the end of the frame as shown in Fig. 1. Hence, each node transmits in the previously assigned time slot with duration of T_s seconds. We consider that the system has N_c nodes for the continuous monitoring for EEG and ECG studies while there are N_e nodes for the EGG event reporting data. The model used in this work considers the arrival rate of the event, i.e., the number of events per second (cases when the sensed values of the EGG signal lies outside the *normal* values, as specified by the medical team). Specifically, we consider that there are λ_e events per second. Also, an exponentially distributed random variable for the occurrence of the events is considered. As such, we assume that the inter-arrival time of events is $1/\lambda_e$ seconds per node.

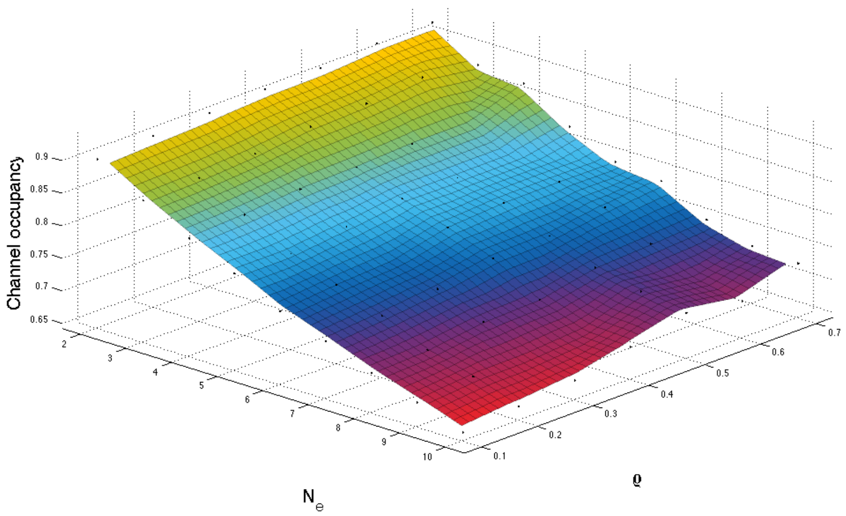

Fig. 2. Channel occupancy for $\lambda_e = 0.3$

Additionally, the model explicitly considers that not all events are correctly detected. Indeed, in an ambulatory system where patients can walk or have

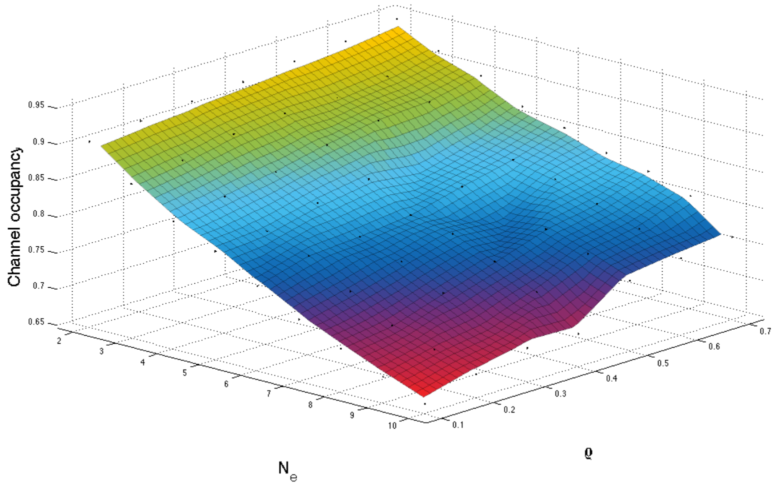

Fig. 3. Channel occupancy for $\lambda_e = 0.5$

movements it is likely that some events are not correctly detect due to the misplacement of nodes or even because of the type of the sensor used or external variables, such as sweat or clothes. This is modeled though the use of ρ which is defined as the conditional probability that given that an event occurred, it is detected by the node.

The system is evaluated in terms of the channel occupancy. Delay is not considered since it is clear that each node can transmit in the pre-assigned time slot in the frame. Hence all nodes can transmit each $(N_e + N_c)T_s$ seconds. In this case, this reporting delay is constant.

Channel occupancy is the average number of time slots used in the frame divided by the total number of time slots. Since events occur randomly in the system, and they are not always detected, we are interested on investigating the performance of the system in terms of the resource wastage, or resources not used for different environments. In particular, Fig. 2 shows the channel occupancy for $\lambda_e = 0.3$ while Fig. 3 and 4 are for $\lambda_e = 0.5$ and 0.7 respectively.

Evidently, channel occupancy takes values between 0 and 1. In these experiments, we observe the system behavior for different number of event nodes and detection probability. From these figures it can be seen that as the value of ρ increases, also the channel occupancy increases since nodes detect correctly each event. On the other hand, as the value of the number of nodes increases the channel occupancy decreases. This is because the more time slots assigned to the event detection at the end of the TDMA frame, the more slots that are not used when an event is not present. Hence, more bandwidth wastage occurs.

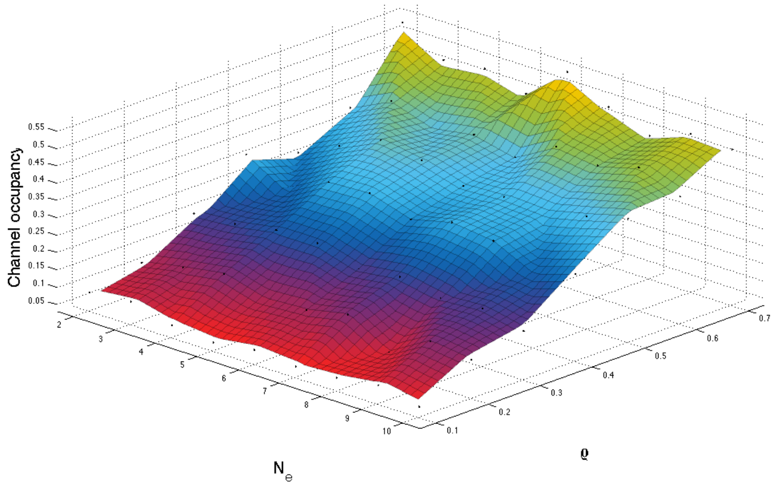

Fig. 4. Channel occupancy for $\lambda_e = 0.7$

2.6 Multiple Event Detection

In the previous analysis, all nodes were assumed to have the same detection probability ρ. We believe that this is accurate in the case that all nodes are in a similar placement in the patient. However, in the case that nodes are placed in different parts of the body in different conditions, this might not be true. On the other hand, other types of nodes can be used in the system. For instance EGG signals can be monitored using different types of nodes. In this case, the detection probability may be different for each individual node. We model the case where each type of node i has a different detection probability ρ_i. For example, we consider three different types of nodes such as: ρ_0, $\rho_1 = \alpha\rho_0$, $\rho_2 = \beta\rho_0$ where α and β are values that vary in the range of 0.1 to 1. In Figs. 5 and 6, the channel occupancy is plotted for $\rho_0 = 0.1$ and 0.5 respectively and with $\lambda_e = 0.8$. From these results it can be seen that the different values of the detection probabilities has an important impact on the channel occupancy. As expected, as the value of α and β decreases, the occupancy also decreases since there are more empty slots by node that do not detect the event.

3 Preemptive System

In view of the bandwidth wastage produced by the non-preemptive scheme, we now propose a preemptive scheme where nodes reporting event information, i.e. EGG data, use the assigned times slots to continuous monitoring nodes. The rationale behind this scheme is that we consider that event data information has priority over continuous monitoring data. As such, we propose to turn on and

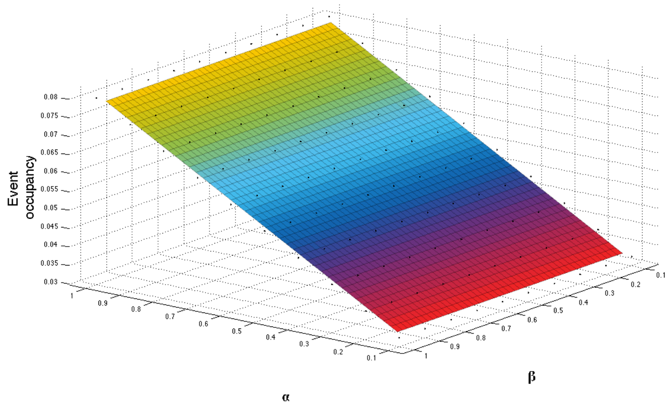

Fig. 5. Event occupancy for $\lambda_e = 0.8$ and $\rho_0 = 0.1$

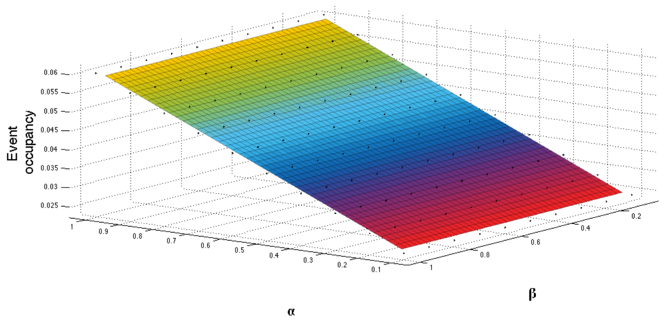

Fig. 6. Event occupancy for $\lambda_e = 0.8$ and $\rho_0 = 0.5$

off the continuous monitoring nodes in order to have empty slots that can be used by event reporting nodes. As such, some continuous monitoring data is no longer transmitted to the sink node (when the node is off) losing information. In this sense, the proposed mechanism is preemptive. To this end, we propose to use a Cognitive Radio Network composed of a primary network (the continuous monitoring nodes) while a secondary network (nodes in the event reporting scheme) uses the time slots not being used by the primary network. Note that continuous monitoring nodes always use their assigned time slot whenever they are actively transmitting. However, event reporting nodes have to scan all the possible channels in order to identify an empty slot and transmit their information.

It is important to notice that the time that a continuous monitoring node remains in the on and off modes has a major impact on the performance of the system. On one hand, the more time nodes remain in the on mode, more continuous information is relayed but event reporting nodes find less available channels to transmit their information and viceversa. Building on this, we propose to use randomly exponentially distributed times for continuous monitoring nodes to remain in the on and off modes in order to study the system's performance. In more detail, continuous monitoring nodes remain active (on) an average time of $\frac{1}{\gamma}$ seconds while they remain in the sleep mode (off) in average $\frac{1}{\delta}$ seconds. This cognitive radio system is depicted in Fig. 7

The system performance is studied in terms of successful event reporting which reflects the capacity of the secondary network to find empty slots from the primary network. Additionally, the energy consumption is obtained.

For the successful event reporting, Figs. 8 and 9 present the probability that an event is successfully transmitted to the sink, i.e., the probability that a node in the secondary network finds an empty time slot to transmit its information. In these figures, it can be seen that as the average time that nodes remain in sleep mode increases (low values of δ) and the average time that nodes remain in the active mode decreases (high values of γ) the event reporting probability increases since it is more easy to find empty slots. Conversely, when δ is high an γ is low, there are very few opportunities to transmit event data. Comparing a scenario with low event reporting, such as the one presented in Fig. 8, to a scenario with high event reporting, such as the one presented in Fig. 9, it can be seen that in the successful event reporting decreases in a high event occurrence case. Again, this is because there are less available resources in the system. Note that the event occurrence (the value of λ_e) is determined by the specific condition of the patient and it is not a parameter controlled by the network.

It is important to note that the adequate value of the successful event reporting has to be set by the medical staff since they can adjust the value of δ and γ in order to have a functional system. For instance, for a particular patient, the medical staff can determine that a successful event reporting of 0.8 might be

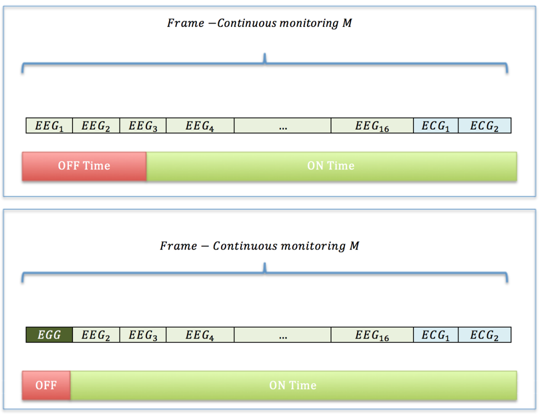

Fig. 7. TDMA-based protocol with ON/OFF processes

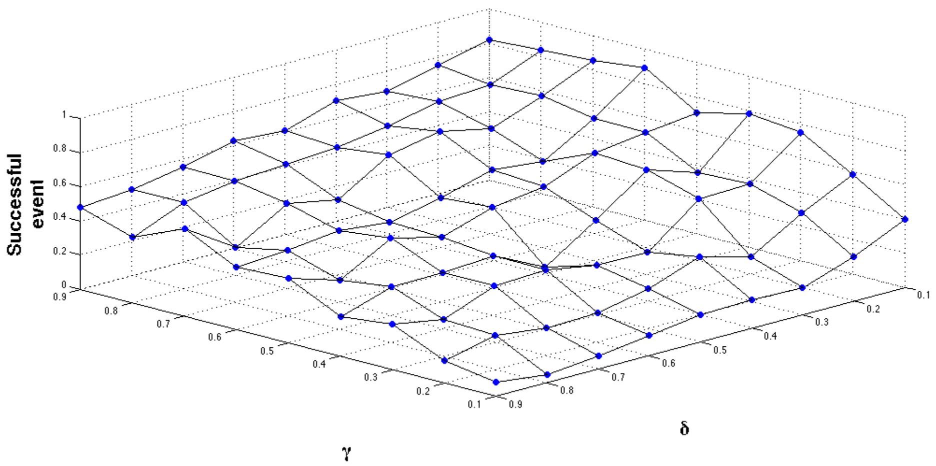

Fig. 8. Probability of successful event for $\lambda_e = 0.25$ and $\rho = 0.25$

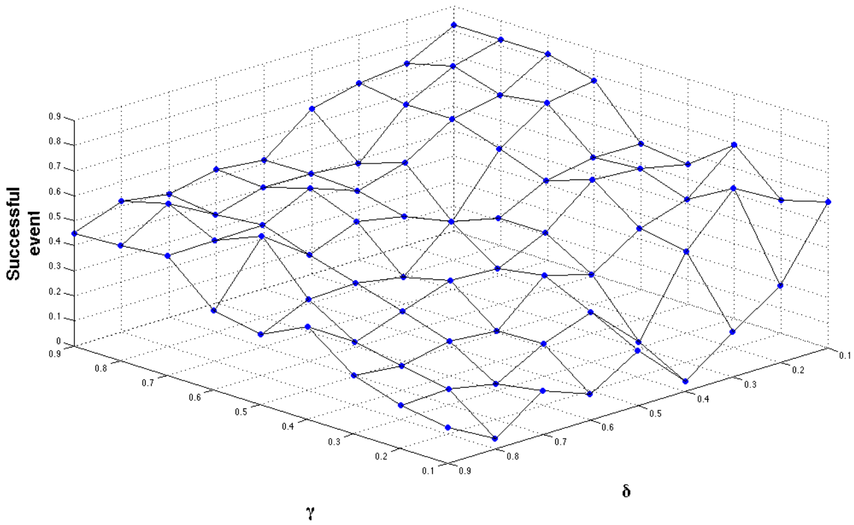

Fig. 9. Probability of successful event for $\lambda_e = 0.95$ and $\rho = 0.95$

sufficient, while other patient may require a probability of 0.9. These values may be adjusted according to the medical history or age of each individual patient.

As for the energy consumption, Figs. 10-12 show the energy consumption for the event reporting, for the continuos monitoring and the total energy consumption in the network respectively considering a value of $\rho = 0.5$ and different event arrival rates. The more that nodes in the continuous monitoring remain

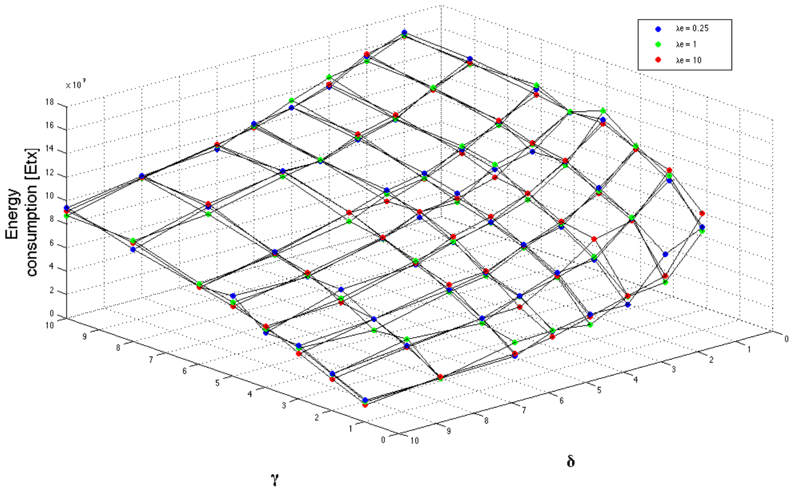

Fig. 10. Successful event energy consumption for $\rho = 0.5$

in the sleep mode the less energy they consume while the event nodes consume more energy since there are more event transmissions. And the same is true for the total energy consumption.

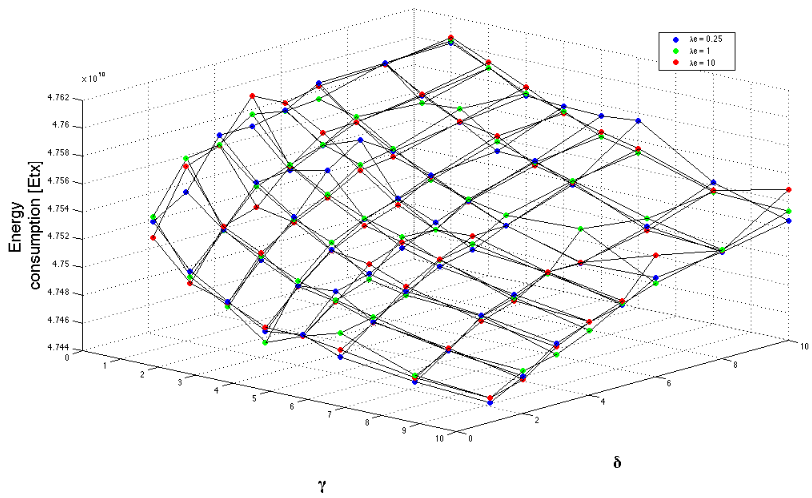

Fig. 11. Continuous monitoring energy consumption for $\rho = 0.5$

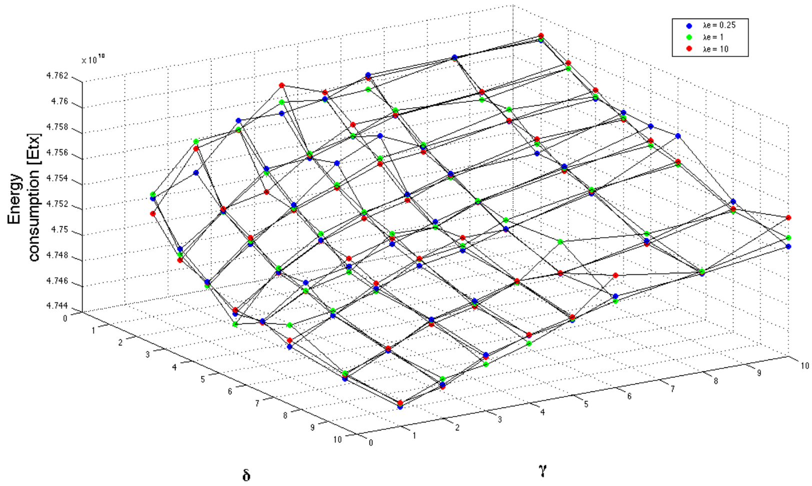

Fig. 12. Total energy system consumption $\rho = 0.5$

4 Conclusions

In this paper a hybrid wireless sensor network for the detection of epilepsy is proposed and studied. The network is capable of transmitting information regarding the EEG, ECG using a continuous monitoring scheme while the EGG signals are transmitted via an event detection scheme. Two different techniques are proposed. Namely a non-preemptive technique that does not lose information but produces bandwidth wastage and a preemptive scheme that allows some information losses but with a better channel utilization. The selected scheme in a practical implementation would heavily depend on the medical needs and conditions of the patients. The system is studied in terms of channel occupation, successful event reporting and energy consumption for different scenarios of event arrivals and event detection probabilities.

From the results obtained in this work, it can be concluded that both schemes, the preemptive and non-preemptive schemes are well suited for the transmission of the EEG, ECG and EGG signals. However, the non-preemptive scheme requires higher data rate transmissions while it consumes more energy and entails resources wastage while the non-preemptive scheme consumes less energy and uses more efficiently the data channels but it entails some information loss.

References

1. Serratosa, J.; Casas, C.; Gil-Nagel, A.: Evidencia científica en epilepsia. Manual de Actuación. Organización médica colegial de España

2. Martinez, S.; Rivero, M.; Garay, L.: Design of Hybrid Wireless Sensor Network to Monitor Bioelectric Signals Focused on the Study of Epilepsy. Research in Computing Science, Instituto Politécnico Nacional, 75, 43-49 (2014)
3. Chung, W. Y.; Lee, Y. D.; Jung, S. J.: A Wireless Sensor Network Compatible Wearable U-healthcare Monitoring System Using Integrated ECG, Accelerometer and SpO2. Institute of Electrical and Electronics Engineers, 8, 1529-1532 (2008).
4. Sivaraman, V.; Grover, S.; Kurusingal, A.; Dhamdhere, A.; Burdett, A.: Experimental study of mobility in the soccer field with application to real-time athlete monitoring, Institute of Electrical and Electronics Engineers, 6, 337-345 (2010)
5. Ganong, W.: Fisiología médica. El manual moderno S.A. de C.V.
6. Enderle, J.; Blanchard, S.; Bronzino, J.: Introduction to biomedical engineering. Elsevier academic press (2004)
7. Dargie, W.; Poellabauer, C.: Fundamentals of Wireless Sensor Network. John Wiley & sons Ltd (2010)