

MAC Protocol for UWB Wireless Body Area Network

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Abstract

Wireless Body Area Network (WBAN) is a networking concept that has evolved with the idea of monitoring vital physiological signals from low-power and miniaturized in-body or on-body sensors. Since WBAN sensor nodes are battery powered, they should be low power devices. The sensor tier communication of a WBAN involves the co-existence of WBAN hardware and Medium Access Control (MAC) protocol that enable the efficient communication of sensor data. The main focus of this paper is to investigate key aspects of MAC protocol used in WBAN systems focusing on Ultra Wideband (UWB) as the wireless technology, paying attention to its ability to cater to the need of high data rate while operating at a low power. MAC protocol mentioned in this paper have considered manipulation of the physical layer properties of the UWB systems such as number of pulses per data bit (PPB), which can be incorporated with the MAC algorithm in order to make the system more dynamic in terms of Bit Error Rate (BER), data rate, and Quality-of-Service (QoS).

Keywords: MAC; UWB; WBAN.

1. Introduction

The advance in technologies has improved the quality and efficiency of health care services; also the increasing use of wireless networks and the constant miniaturization of electrical devices have empowered the development of WBANs. A WBAN consists of small, intelligent devices (bio-sensors) attached on or implanted in the body which are capable of establishing a wireless communication link. These devices provide continuous health monitoring and real-time feedback to the user or medical personnel. The sensors of a WBAN measure different vital signs, for example the heart rate, the body temperature or Electrocardiogram (ECG) [1].

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The basic requirements of a WBAN are: support of scalable data rates, low power consumption, small form factor, controllable transmit power, ability to prioritize data transmission of crucial signals, secure data transmission, coexistence with other wireless technologies, ability to operate in multi-user environments, and limited transmission range (0.1–2 m) [2].

Several key components can be identified in a WBAN system for health care monitoring applications. Sensor nodes are either implantable or wearable devices that transmit vital physiological information to an outside remote node. A coordinator node or sink node is used to collect, analyze, and route the information sent by sensor nodes and forward this information to a computer-based application for interpretation. Figure 1 illustrates the key components of a WBAN.

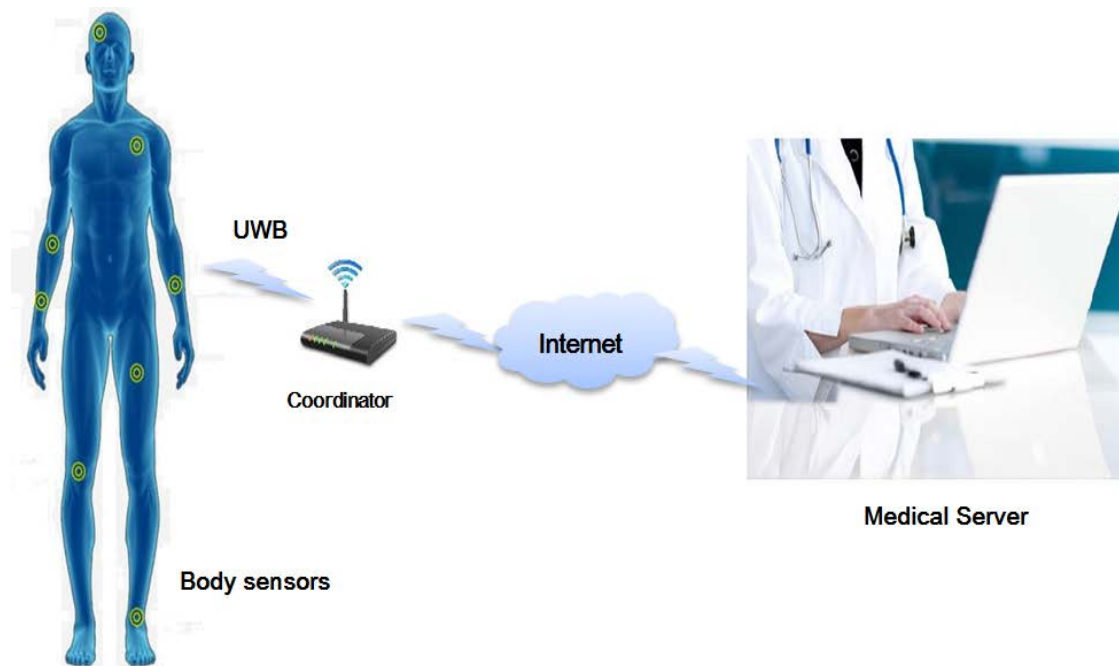


Figure 1: WBAN architecture

Medical sensors involved in WBAN communication are battery operated. Hence, they should consume low power. This paper presents UWB as a suitable wireless technology to achieve high data rates while keeping power consumption and form factors small. Although UWB transmitters are designed based on simple techniques, UWB receivers require complex hardware and consume comparatively higher power. It is possible to overcome this drawback by using a less complex narrowband wireless technology for the receiver. Furthermore, an optimized low complexity MAC protocol should be used in WBAN so that it would enhance the low power operation of the sensor node, which is explained and analyzed in this paper.

UWB is a novel wireless short-range technology. According to Federal Communications Commission (FCC), UWB communications operate in 0–960 MHz and the 3.1–10.6 GHz bands. UWB signals have a fractional bandwidth larger than 0.2 or at least 500 MHz. Since UWB systems use ultra-wide bandwidth, the transmission rate of UWB systems can go up to 20 Mbps. In the same time, the emission power of UWB must be kept below

-41.25 dBm/MHz. As a result, UWB devices can enjoy a much longer operating time with a battery. On the other hand, low power transmission of signals limits the communication range (usually 0.1–2 m). UWB system utilizes short digital pulse (impulse radio) for transmission [3].

This paper presents the implementation of UWB MAC protocol that provides efficient data transmission in WBANs applications. The proposed MAC protocol in this work is unique in the sense that it is developed to enhance the performance of a WBAN using the high data rate offered by the UWB transmission. In the proposed MAC protocol herein, priority of data is taken into consideration and a guaranteed delivery mechanism is utilized to transfer data with high priority.

The paper is organized as follows: Section 2 describes a superframe structure of the proposed WBAN. Section 3 describes BER analysis for multiple PPB of UWB transmission. Section 4 discusses the determination of PPB Values by Parent Node. Section 5 presents the implementation of MAC Algorithm for UWB WBANs applications. Finally, Section 6 concludes the paper.

2. Superframe Structure

The MAC layer provides service to the upper layers and enables the transmission and reception of MAC protocol data units (MPDU) across the PHY data service. Features of the MAC layer include beacon management, channel access, guaranteed time slots (GTS) management, frame validation, acknowledged frame delivery, association and disassociation.

A beacon-enabled superframe structure is considered for the UWB WBAN MAC protocol. The network topology for the simulated system is developed based on a simplified version of the IEEE 802.15.4/4a beacon-enabled star topology with modifications added to make it better suited for low power UWB transmission [4].

In the networks with the star topology, the coordinator periodically emits a special frame or packet known as the beacon frame. The time between two successive beacon frames is known as the superframe or (more precisely) as the beacon interval. The format of the superframe is defined by the coordinator [5]. The beacon frame is sent at the beginning of each superframe and contains synchronization information, network configuration information, BAN identification and information about the structure of the superframe.

A WBAN consists of two types of sensor nodes depending on their data transmission rate. Oxygen Saturation (SO₂) and Electroencephalogram (EEG) are continuously transmitting sensors that require high data transmission rate and high guarantee of delivery. These signals can be classified as critical parameters and the MAC protocol is designed to prioritize the delivery of such data. Sensor nodes that transmit heart rate, temperature, sugar level and blood pressure are periodic sensors and do not require high data rate [6].

A superframe is subdivided into two regions, namely active and inactive periods. The active period is further divided into 16-time slots. Based on the MAC layer configuration, these time slots are divided into a Contention Access Period (CAP) and a Contention Free Period (CFP). During the CAP, periodic sensor nodes contend for transmission with the coordinator using ALOHA scheme [7].

The CFP follows the CAP. The CFP offers GTSs. In some applications, contention-based access may not offer adequate performance due to uncertainty caused by collisions. When continuous sensor node needs contention-free access, it can request a GTS of appropriate duration. The coordinator then decides whether to accept or reject the request. If the request is accepted, the node can use the bandwidth provided by the GTS for contention-free communication with the coordinator; other nodes are not allowed to transmit any data at that time (granted exclusive access to the medium). A total number of seven GTS may be assigned. The coordinator must ensure that all GTSs are contained within the CFP period at the end of the active portion of the isuperframe. Following the CFP is the inactive period. During this time, all nodes including the coordinator node may enter a low power mode [5].

The total length of the superframe including the beacon is kept at 1 ms. Two initialization slots of fixed 20 μ s duration are allocated at the beginning of the superframe for sensor initialization. The CAP for each superframe starts after a fixed 35 μ s beacon guard slot from the end of the beacon period. A fixed guard period of 5 μ s is allocated at the end of each time slot. This superframe structure is shown in figure 2.

The synchronization beacons are sent using the narrowband channel in parallel with the UWB transmission in order to reduce the data rate requirement of the narrowband feedback. Narrowband beacon duration of 0.210 msi is used in the simulations, which contains 4 bits transmitting at 19.2 kbps [8].

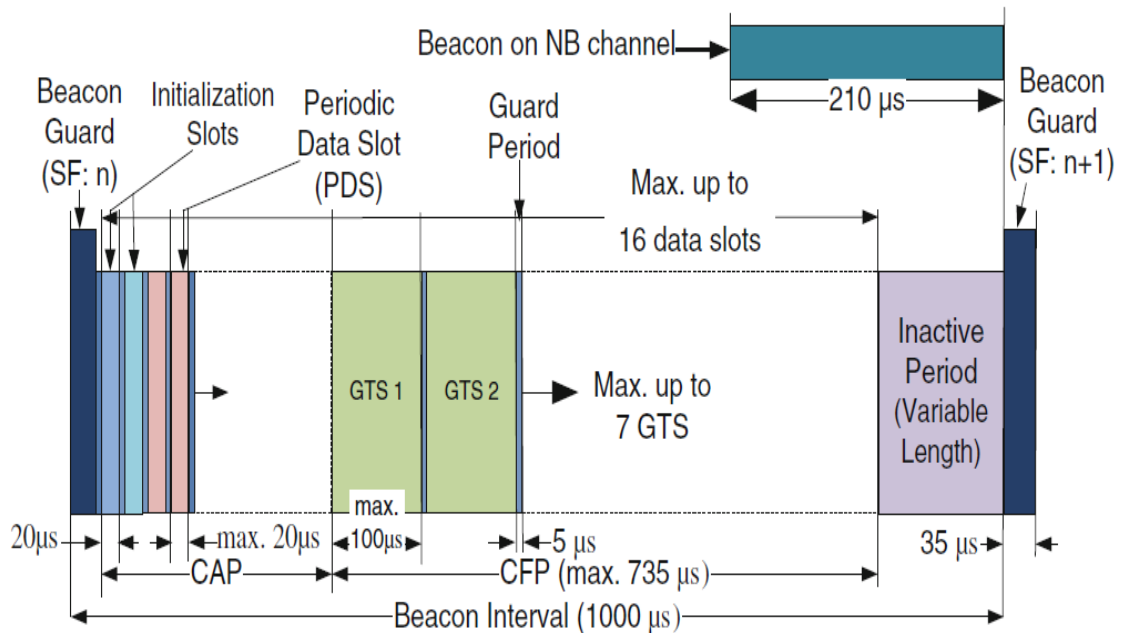


Figure 2: Superframe structure

3. BER Analysis of Multiple PPB Scheme

The transmit power consumption of sensor nodes used in the simulation is determined by the number of PPB value determines the number of UWB pulses sent within the bit transmission slot, which determines the energy consumption within the transmission slot. Figure 3 depicts the use of 2 and 3 PPB schemes for sending data bits.

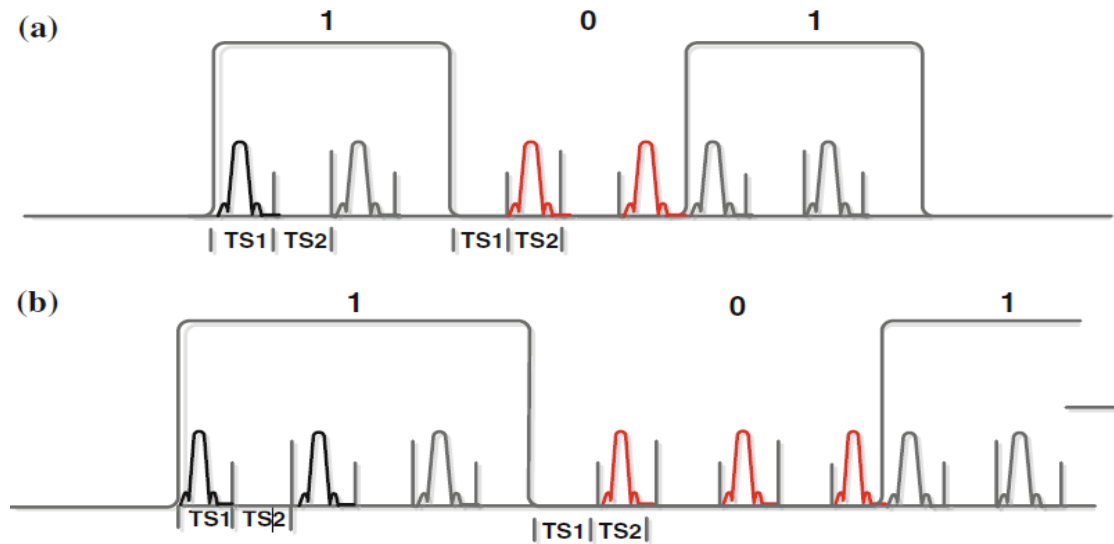


Figure 3: Pulse train for '1' '0' '1' bit pattern using (a) Two PPB and (b) Three PPB

The bit errors in a WBAN environment mainly occur due to multipath interference and random fading of the UWB signal that originates from reflection from various surfaces and different absorption characteristics of objects, such as various body surfaces and indoor equipment [3].

Since the power required to transmit a data bit is equal to the summation of the power of a number of pulses sent to represent that data bit, a considerable power saving can be achieved if the allocation of the number of PPB can be dynamically changed according to the minimum BER requirement at the receiver end.

Assume that two identical sets of data are transmitted using the same transmit power and same separation distance in a realistic WBAN environment that is susceptible to multipath interference and random fading with one data set transmitted using a higher PPB value and the other with a lower PPB value. The transmit signal with higher PPB transmission results in a lower BER than a lower PPB transmission for the same separation distance in a realistic environment with fading and multipath interference.

The most popular form of digital modulation used for UWB systems is pulse position modulation (PPM). This provides the best performance in terms of modulation efficiency and spectral performance and results in significant power savings. It is therefore more suitable for battery operated WBAN applications.

Probability of error for single pulse detection of the receiver with PPM modulation scheme can be derived from [9]:

$$Pe = Q \left(\sqrt{\frac{(Ep/No)^2}{2 (Ep/No + Ts B)}} \right) \quad \dots (1)$$

Where Pe is the probability of error, B is the signal bandwidth of 1 GHz, Ts is the integration period which is equal to the pulse width of 2 ns for the simulations, Ep is the received signal energy during the 2 ns integration period (Ts) and $Q(\cdot)$ represents the Q function.

When multiple PPB is sent, it is assumed that a bit is erroneous when more than half the pulses sent per that bit are erroneous. If N pulses are sent per bit, the probability that a bit is erroneous can be obtained by:

$$P_{\text{bit}} = 1 - \sum_{i=1}^{\lfloor \frac{N}{2} \rfloor} \binom{N}{i} p^i (1-p)^{N-i} \quad \dots (2)$$

Where $p = P_e$, $\binom{N}{i} = \frac{N!}{i!(N-i)!}$ and $\lfloor \frac{N}{2} \rfloor$ is the inferior integer part of $\frac{N}{2}$. Modulation curves showing BER for different number of PPB are obtained based on (2) and presented in figure 4. It should be noted that the BER is plotted against pulse E_p/N_0 in this figure. Bit energy can be obtained by the summation of pulse energies that represent the bit. The results in figure 4 show that for the same E_p/N_0 , sending more number of PPB results in lower BER.

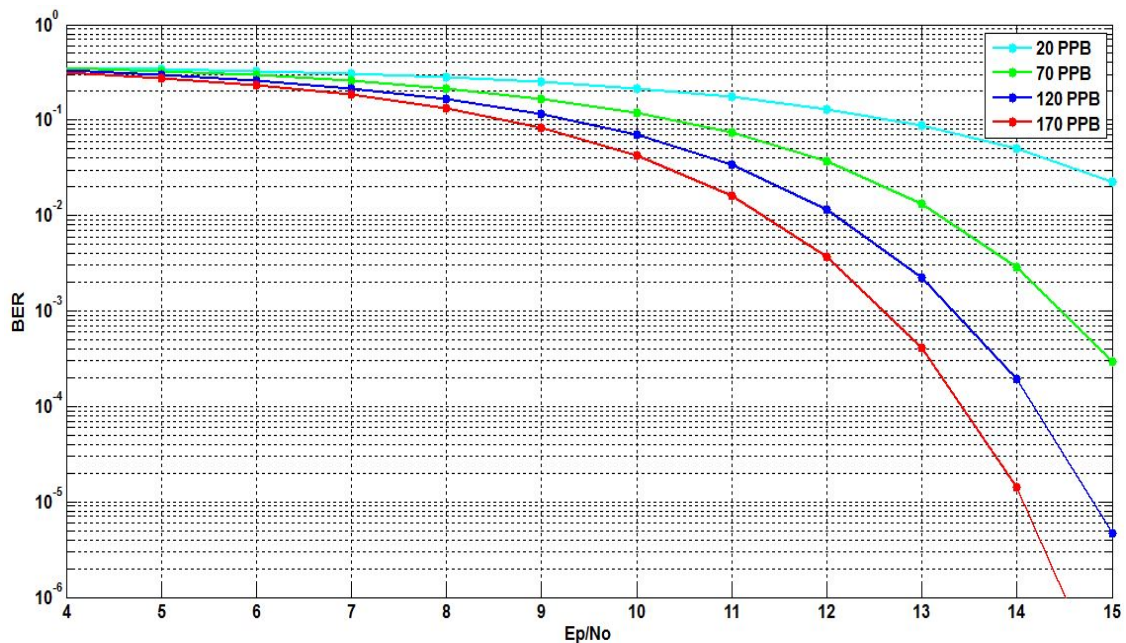


Figure 4: BER versus pulse E_p/N_0 (dB) curves for different number of PPB

4. Determination of Pulses per Bit Values by Parent Node

The PPB value is dynamically changed, by varying the bit duration of the bits generated using a microcontroller of a sensor node, in order to optimize the power consumption of the sensor node.

In the WBAN system described in this paper, a parent node dynamically assigns the number of PPB for a child node in order to obtain a specified optimum BER value at the receiver. A BER threshold of 10^{-4} is used in the simulation scenario for all sensor nodes, because a good throughput can be obtained with this value while keeping the power consumption at the sensor nodes low. During the data transmission, the sensor nodes insert a certain number of bytes containing a known 10-bit pattern of "1011001110" equally spread among the data bits. For the simulations, six bytes are chosen for continuous sensors while three bytes are chosen for periodic sensors. A parent node dynamically determines the BER for a particular sensor node using the known bit pattern

and compares it against the 10^{-4} threshold. Sensor nodes start data transmission with the highest allowable PPB value for that particular sensor type during an allocated transmission slot for that sensor node. Coordinator node requests a particular sensor node to dynamically reduce the PPB value in 1 PPB steps until a BER value of 10^{-4} or the closest possible value is achieved using the minimum PPB value possible. This procedure ensures that the sensor nodes transmit data using the minimum achievable PPB while maintaining a close to 10^{-4} . The sensor nodes resend the same data packet until an agreement is made to use a certain PPB value for future data transmissions. In the case of degradation in the BER during data transmission using the pre-agreed PPB; parent node repeats the above process to increase the PPB value to improve the BER.

This can be achieved in the MAC layer. As a result, a single receiver node can be utilized for all the sensor nodes. The dynamic BER compensation procedure described above is particularly useful in short range UWB communications systems where a strong Line-of-Sight (LOS) path is present, such as the WBAN system described in this paper, to achieve reliable communication during dynamic channel conditions. This result shows that the dynamic PPB scheme described above ensures that sensor nodes always transmit at the minimum PPB value while maintaining an acceptable BER level. This mechanism enables the sensor nodes to operate at optimum power consumption while maintaining a reliable data communication link. Thus, it improves the performance of a UWB communication system.

5. Medium Access Control Algorithm

A WBAN should operate with minimum power consumption while providing reliable data transmission. Design an efficient MAC protocol plays a vital role in reducing power consumption and increasing the reliability of data transmission. It is vital to utilize the unique physical properties of a UWB signal, such as the possibility to send multiple numbers of pulses to represent a data bit, in order to improve the system performance and overcome the drawbacks such as high receiver complexity. Two different addressing levels are required in order to identify the sensor nodes used in the WBAN. One addressing level identifies the patient while the other addressing level identifies the different sensors that belong to the same patient. A sensor node synchronizes to the superframe structure used in the MAC protocol by listening to the beacon packets transmitted on the narrowband channel. All the sensor nodes are initialized during the first two time slots of the superframe using random access. Continuously transmitting sensor nodes will request for GTS from the coordinator during the initialization. As a response to this request, the coordinator will permanently assign a time slot in CFP for that particular sensor node. Periodic sensor nodes will transmit using random access during the CAP slot. Figures 5 & 6 & 7 depict the algorithms used for sensor initialization and data transmission of continuous and periodic sensors. At sensor initialization, a sensor node uses the maximum allowable PPB value in order to transmit an initialization request message and starts a time-out operation in order to determine whether the sensor node gets an initialization response from the coordinator node within a given amount of time. A known bit pattern appended by a predefined sensor address and sensor type flag (continuous or periodic) is sent in the initialization request. Sensor node then waits until the reception of initialization acknowledgment packet that contains transmit time slot and maximum allowable PPB value. If a time-out occurs without receiving the initialization acknowledgment packet, sensor node then retransmits an initialization request message during the initialization slots of the following superframe. The maximum number of initialization attempts is limited to 10. After

initialization, a sensor node goes through a BER compensation period where sensor node and coordinator node negotiate a final PPB value to be used for that particular instance in order to transmit at a minimum possible PPB value while keeping the BER below or equal to 10^{-4} (as discussed in section 4) and data transmission continuous. Because this MAC protocol has the ability to change the number of pulses per data bit in real-time, it is possible to cater variable data irate requirements while keeping the network utilization at a maximum level for high priority sensor nodes. A scalable data rate of up to 5 Mbps can be achieved using this MAC protocol depending on the number of pulses per bit and pulse transmission interval.

6. Conclusion

This paper presents a UWB MAC protocol that provides efficient data transmission in WBANs applications. This MAC protocol uses a beacon enabled superframe structure in order to schedule the data transmissions of sensor nodes; hence reduces the multiple access interference in the network. Furthermore, it is designed to dynamically control the Pulses Per Bit (PPB) value used for UWB data communication using control messages sent via the narrowband feedback path. This leads to dynamic BER and power control at the sensor nodes, which helps to improve the reliability of communication and power efficiency of sensor nodes under dynamic channel conditions.

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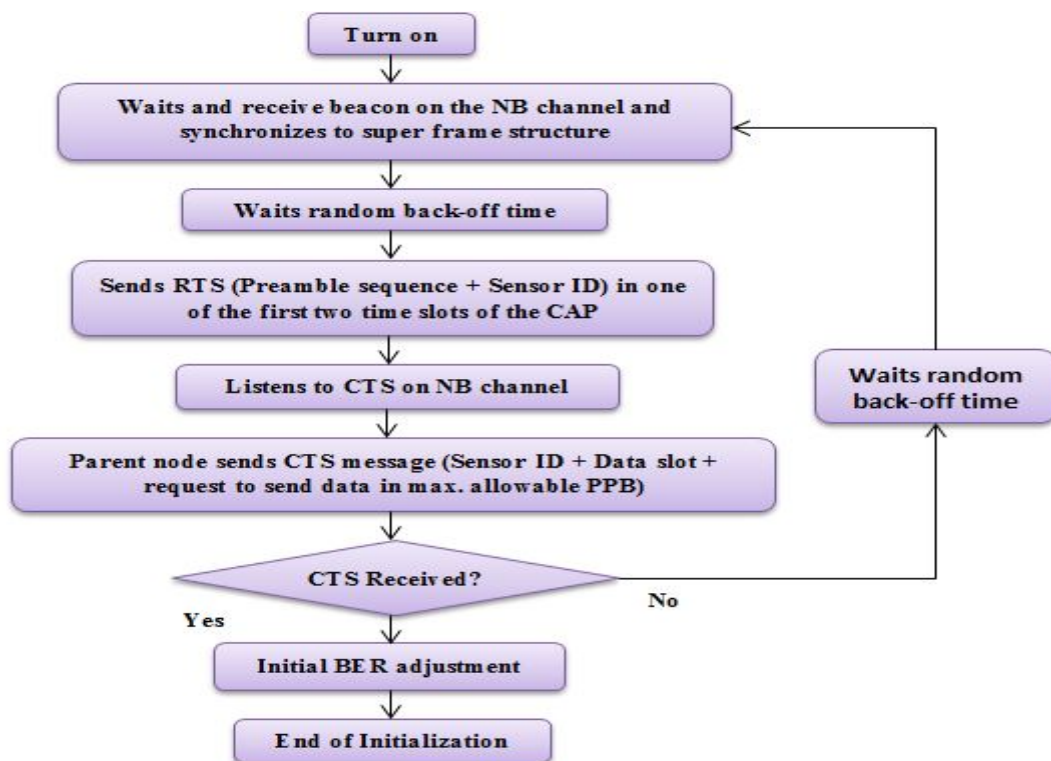


Figure 5: Sensor initialization procedure

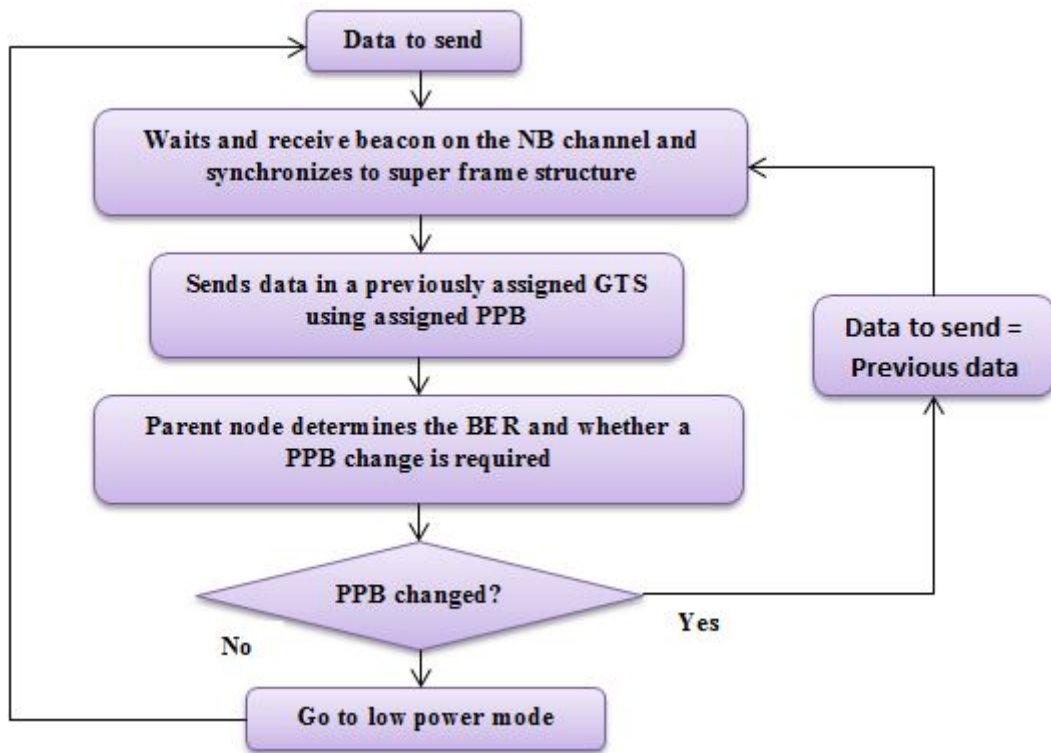


Figure 6: Algorithm for data delivery of continuous sensors

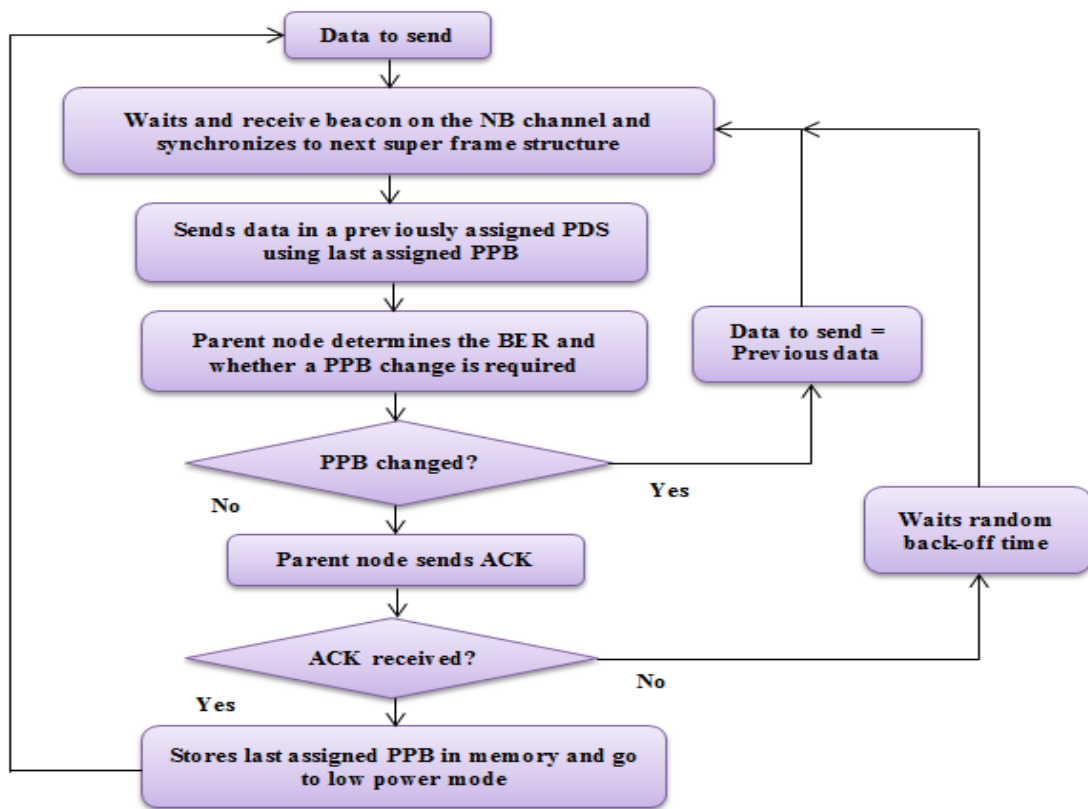


Figure 7: Algorithm for data delivery of periodic sensors

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