Cognition-Based Delay Analysis to Determine the Average Minimum Time Limit for Wireless Sensor Communications

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SUMMARY End-to-end delay, aiming to realize how much time it will take for a traffic load generated by a Mobile Node (MN) to reach Sink Node (SN), is a principal objective of most new trends in a Wireless Sensor Network (WSN). It has a direct link towards understanding the minimum time delay expected where the packet sent by MN can be received by SN. Most importantly, knowing the average minimum transmission time limit is a crucial piece of information in determining the future output of the network and the kind of technologies implemented. In this paper, we take network load and transmission delay issues into account in estimating the Average Minimum Time Limit (AMTL) needed for a health operating cognitive WSN. To further estimate the AMTL based on network load, an end-to-end delay analysis mechanism is presented and considers the total delay (service, queue, ACK, and MAC). This work is proposed to answer the AMTL needed before implementing any cognitive based WSN algorithms. Various time intervals and cognitive channel usage with different application payload are used for the result analysis. Through extensive simulations, our mechanism is able to identify the average time intervals needed depending on the load and MN broadcast interval in any cognitive WSN.

key words: broadcast load balancing, delay, cogitative, interference, wireless sensor network

1. Introduction

Although, WSNs are successful in providing excellent services using a limited resource and gathering information with smaller devices. These networks are very vulnerable for collusion, delay, and packet loss that is if used without considering the AMTL. The major problem lays in having information not only about the broadcast latency of MNs but also understanding the average minimum channel access time interval of end devices communicating in the network. AMTL information regarding the end devices is an essential parameter in determining the QoS of a network and spectrum sharing mechanisms to be used [1]. If we need an efficiently working WSN environment, the baseline is simple that having full information about the number of end devices communicating a WSN coordinator and the average minimum time interval in which these end devices send data to their central coordinator.

Enormous WSN techniques explained on how to increase the number of communicating MNs by sharing spectrum, time, and power [2]–[5]. But, in none of the listed references that AMTL is under consideration. Even though those are the principal factors for most of current cognitive WSN based algorithms, it is good practice to consider the AMTL of data reception during any WSN algorithm design.

One of the common problems that we noticed is that most of the researchers not consider how many nodes supported at a specific average time interval during the design of the cogitative radio-related mechanism. Conventionally techniques like congestion, cognitive radio, and hand-off are used to solve QoS of WSN by minimizing the end-to-end delay. However, if implemented without considering AMTL, all listed solutions may not solve the problem. Because, how much MNs supported in a given average time is a baseline for those techniques. As we are living the age of IoT, dealing with sharing resources [5], [6], we need to know how much we have, how much we left, and when to use different mechanisms in advancing network output. As mentioned by Ref. [7], most real-environment experimental results show that delay in IoT devices varies depending on various circumstances. So, it is essential to evaluate the AMTL for cognitive WSN communication.

Unlike previous works, this work focuses on analyzing the AMTL for applications, which gives a baseline for anyone interested in working with cognitive WSNs. The number of MNs and their AMTL of channel usage are the two principal parameters considered during result analysis with other factors explained in previous works.

Next, we will go through the related work and general scenario used in Sects. 2 and 3 respectively. In Sect. 4, an end-to-end delay derivation presented. Under Sect. 5, we will discuss the performance evaluation. Finally, under Sect. 6, we will conclude our analysis.

2. Related Works

Designing spectrum-time related solutions for cognitive WSNs is challenging since the characteristics of QoS metrics in WSNs are varying for every environment. Due to this nature, probabilistic QoS metrics introduced during the early 2000s [8]–[10]. In these studies, the worst-case analyzed, but it is limited for three main reasons in WSNs: randomness, low power nature of the communication links, and high variance in their end-to-end delay. These motivate the need for general AMTL analysis rather than probabilistic QoS assurance.

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Recently, a large number of works have analyzed the delay distribution of radio transmission errors experienced by wireless channel in wireless multimedia sensor networks (WMSNs) like: [11] for healthcare, [12] for video surveillance, [13] for real-time target tracking, and [14] for habitat monitoring. However, AMTL needed by wireless channels in cogitative WMSNs makes it hard to achieve these qualities simultaneously. Therefore, it is great to have a good understanding of the factor, AMTL.

A lot of research has been carried out on developing delay calculation methods [15]–[18]. These works mainly focus on evaluating the general average delay time needed in WSN. On the other hand, some researchers focus on WSN dimensioning by a mathematical tool called network calculus [19], and they care about the worst-case performance of WSN. But in our method, we considered the general condition not only the worst scenario.

3. General Scenarios

Design considerations are formulated to bring and implement the most general manners of WSN application assumptions in practice. The crucial points throughout the entire implementation process are: beacon-enabled WSN where whole licensed channels are assumed to have the same channel gain, data packets are sent from different MNs to a CN, every communication recorded in order to check success, consider N-number of CN, one SN and N-number of MNs in a star topology, 6 consecutive channels are used for result analysis and various time intervals used for result collection.

As seen in Fig. 1, during each step of communication, we record the values for significant delays (Queue, MAC, Service, and ACK delays). Then the total delay is calculated by adding all delay values recorded starting from sending MN to the whole way to destination SN. All participating devices own all types of delays except that the SN node has no queuing delay. The value ACK delay displayed in the result part is the sum of all ACK delays registered from the origin up to the destination and the same wise for the queue, service, and MAC delays.

Because the objective is for cognitive-based delay analysis, energy detection is performed when every packet reception is completed. The cognitive algorithm presented in our previous work [3] is applied. Spectrum sensing, selects the available licensed channel and broadcasts selected channel to all MNs through the periodical beacon frame is the responsibility of CN.

Also, we considered an arbitrary data packet of 16 to 250-bytes from different nodes at a given time interval of Poisson distribution, \( \alpha \). Every node sends the same data a hundred times (100x) using \( \alpha \) interval. With 2-10 number of licensed users are executed for each result collection.

The purpose of this work is to analyze the possible number of MNs supported within a specific time delay limit of \( \alpha \) in cogitative radio-based WSN. Finally, we can rationally reconstruct the approximated execution to determine how network load and delay are adjusted and use the result as a reference.

4. End-to-End Delay Derivation

In this section, our proposed method to calculate the end-to-end delay presented. Calculation of the AMTL value considers four main delays: 1) service delay, 2) queuing delay, 3) MAC delay, and 4) ACK delay. Where \( \alpha \) represents the Poisson distribution based packet generated during experiment Ref. [20] while \( S_{\text{delay}} \), \( Q_{\text{delay}} \), \( D_{\text{MAC}} \) and ACK\( T \) represent four delays, respectively. Only \( S_{\text{delay}} \), \( D_{\text{MAC}} \) and \( Q_{\text{delay}} \) are explained in the following sections considering that ACK\( T \) is constant so simply adding it to the total time derived.

\[
\text{Delay} = \alpha (\text{ACK} T + D_{\text{MAC}} + S_{\text{delay}} + Q_{\text{delay}}).
\] (1)

Below, we present the details for \( S_{\text{delay}} \), \( D_{\text{MAC}} \) and \( Q_{\text{delay}} \) delay derivation.

4.1 \( S_{\text{delay}} \), Service Delay Derivation

We measured the service delay which is described as the continuation that unlicensed user data packet is successfully transmitted to its sink node. Regarding licensed once they are served as soon as they need without any service delay time [3].

Figure 2 Explains the most common steps that an unlicensed user packet transmission transmitted successfully on channel CH \((11, 12, \ldots, 26)\). From the figure, C(i) and B(i) denotes the unsuccessful transmission time of a packet due to the collision and the busy period of the channel, respectively. Mostly these kind of delays occurred basically due to primary user activities or channel rendezvous. Finally, we have H at the end represents the time that MN transmits a packet successfully without interruptions. The whole process is represented by \( T_d \), the entire duration that the MN
executes a successful transmission of a single packet of an unlicensed user.

\[ T_d = \sum_{i=1}^{n} [C(i) + B(i)] + H. \]  

(2)

Moreover, Poisson process with a service rate of \( \lambda_p \) used for the busy period analysis, due to primary user activity. Every packet transmission time which is a reason for busy channel time (licensed user transmission) follows exponential distribution with expectation of \( H_p \) as described in reference [21]. The service for such traffic is

\[ \mu_p = \frac{1}{H_p} \]  

(3)

where \( \mu_p \) represents service rate of priority activities. The expected value of a busy period, \( B \), on a given communication channel in a specific time interval.

\[ E[B] = \frac{1}{\mu_p - \lambda_p}, \]  

Ref. [21]  

(4)

We assumed that: 1) condition for the unlicensed user transmission interruption due to the licensed user activity is that the idle period on the channel is smaller than the unlicensed user packet length. 2) and \( W \) is the duration, then we obtain the interruption probabilities between unlicensed user transmissions and licensed user as follows:

\[ P(n = N_c|W) = (1 - e^{-\lambda_p})^n e^{-\lambda_p} W, n = 0, 1, 2, \ldots \]  

(5)

\( N_c \) represents the number of collisions. The expected value of \( T_d \) is

\[ E(T_d|W) = E\left[ \sum_{i=1}^{n} [C(i) + B(i)] + W \right] \]

\[ E[N_c]E[C|W] + E[B|W] + W \]  

where \( E[B|W] = E[B] = \text{Eq.}(4) \)  

(6)

\[ S_{\text{delay}} = E(T_d) = E[E[T_d|W]] \]  

\[ = E[N_c(E[H|W] + E[B|W]) + E[W] \]

\[ = \left( \frac{1}{\lambda_p} + \frac{1}{\mu_p - \lambda_p} \right) E[e^{-\lambda_p H} - 1] \]  

(7)

4.2 \( Q_{\text{delay}} \), Queuing Delay Derivation

Figure 3 shows the general queue state of the source MN and the destination nodes, coordinator (CN) and sink node (SN). More, both the source and destination nodes follow a First In First Out (FIFO) buffer strategy.

\[ N \] state discrete Markov chain is considered where \( N > 3 \), but first implemented for the signal-hop cognitive radio WSN is introduced. Explained in Fig. 4, where the source and destination is a multiple hop away. The \( N \) states defined by two parameters: the number of data packets and number of ACK packets in each node.

Three major scenarios of channel usage between the source and destination node are considered: successfully accessed by the source node, \( P_{\text{suc}} \) is the probability that the source node, MN or CN, sends a data packet to the destination node, SN. The destination node accesses successfully, \( P_{\text{ack}} \) denotes the probability that the destination node sends an ACK packet to the source node and we used \( P_{\text{not}} \) to represent the probability of no data packets is transmitted in the current slot. In addition, the steady state probabilities used for all the states and represented by letter \( \beta \).

From conservation law, we get

\[ \beta_{MN} = P_{\text{not}} MN \beta_{MN} + P_{\text{ack}} MN \beta_{CN} \]

\[ \beta_{CN} = P_{\text{suc}} MN \beta_{MN} + P_{\text{not}} CN \beta_{CN} + P_{\text{ack}} CN \beta_{SN} \]

\[ \beta_{SN} = P_{\text{suc}} CN \beta_{CN} + P_{\text{not}} SN \beta_{SN} \]

\[ \beta_{MN} + \beta_{CN} + \ldots + \beta_{SN} = 1. \]  

(8)

which take us to queuing delay equation which is represented by:

\[ D_{\text{queue}} = P_{\text{suc}} MN L_p + P_{\text{ack}} MN L_{\text{ack}} + P_{\text{suc}} CN 2L_p \]

\[ + P_{\text{ack}} CN P_{\text{ack}} MN L_{\text{ack}} + \ldots \]

\[ + P_{\text{suc}} SN 3L_p + P_{\text{suc}} CN P_{\text{ack}} MN L_{\text{ack}}. \]  

(9)

where \( L_{\text{ack}} \) and \( L_p \) represents ACK packet and length of data packet respectively. Finally, we represent \( D_{\text{queue}}(\text{MN}) \), and \( D_{\text{queue}}(\text{CN}) \) as states of delay in our queue.

\[ D_{\text{queue}}(\text{MN}) = P_{\text{suc}} MN L_p + P_{\text{suc}} CN 2L_p \]

\[ + P_{\text{suc}} CN P_{\text{ack}} MN L_{\text{ack}} + P_{\text{suc}} CN P_{\text{ack}} CN 2L_{\text{ack}}. \]
\[ D_{\text{queue}}(CN) = P_{\text{suc}MN}L_P + P_{\text{suc}CN}2L_P + P_{\text{suc}N}3L_P + P_{\text{suc}N}P_{\text{ack}MN}L_{\text{ack}} + P_{\text{suc}N}P_{\text{ack}CN}2L_{\text{ack}} + P_{\text{suc}N}P_{\text{ack}N}3L_{\text{ack}}. \] (10)

The generally queuing delay calculated as:

\[ D_{\text{queue}} = \sum_{j=0}^{x} \left( \sum_{i=1}^{j+N-1} P_{\text{suc}}^i L_P + P_{\text{suc}}^{x+1} \sum_{i=1}^{2j+N-1} P_{\text{ack}}^i L_{\text{ack}} \right). \] (11)

4.3 \( D_{\text{MAC}}, \text{MAC Delay} \)

Finally, we calculated a delay from the moment that a packet reaches a physical layer to the pass through the end of the MAC layer successfully. Therefore cooperative MAC, the physical layer cooperates to MAC layer, considered which improve the throughput in wireless networks [22]. Where Eq. (8) of the same Ref. [22], implemented for four state transition scenario.

\[ D_{\text{MAC}} = \sum_{i=1}^{n_c} T_{ci} + \sum_{i=1}^{n’c} T’_{ci} + T_{si} + \text{Idle time} \] (12)

where \( n_c, n’c \) the number of re-transmissions, collided, successes of full transmissions, finally \( T_S \) and \( T_C \) represent success full and unsuccessful time respectively. Both are multiplied with their corresponding probability, \( pT \)

\[ T_S = \sum_{i=1}^{4} T_{si} \cdot pT_{si} \quad \text{Ref. [22]} \]

\[ T_C = \sum_{i=1}^{4} T_{ci} \cdot pT_{ci} \] (13)

5. Cogitative Algorithm

Besides, hardware and software constraints, an efficient cognitive-channel algorithm must be addressed to achieve adequate network performance in cognitive WSN communication. In our algorithm, the central coordinator notifies MNs about through which node they can communicate during association. Moreover, the effects of the operating environment are taken well care under our algorithm. The inactive portion of communication is used for sensing, channel energy level detection, updating and results saving in a table, TSR, so that we can use it in the future. The whole process is described in our previous work [3]. Using cognitive channels resulted in effective ATMLT due to the fact that it effectively manages the communication spectrum.

5.1 Simulation Based Analysis

To evaluate the performance of the proposed AMTL scheme, we conducted extensive software simulation using OMNET++. The main advantage of performing our proposed scheme using a simulation environment is that it is easy to analyze the type of delays which are challenging to examine in real environment experiments. Some general parameters applied in our simulation are listed below.

### Simulation parameters

| Parameter                      | Value          |
|-------------------------------|----------------|
| Number of MNs                 | 20             |
| Number of channels used       | 6              |
| Transmission range            | 150M           |
| Length of channel sensing period | 1ms         |
| Data rate of the channel      | 2Mbps          |
| Size of all types of ACK packets | 240 bites  |
| Size of data packet          | 16-250 bytes  |
| Simulation time              | 5000 s         |
| Number of executions done     | 3000           |

ACK, queue, service, and MAC delays are the main parameters studied. In the image below we try to show what it look likes the ruining test environment.

First, we showed the results traced for the average minimum queue and service delay times. These are the two most significant delays that any WSN communication experiences. The simulation results in Fig. 7 shows that the largest average minimum delay value registered is queue delay compared to service delay. Obviously, in a high traffic environment queue delay depends on the service delay. The traffic flows are used to build queueing delay at node 1,2,3,…SN which is of interest in our evaluation. Our proposed scheme achieves high accuracy for evaluating AMTL for queueing and service delays in burst network traffic. It’s known that result collection for these parameters in the real environment experiment are more complicated compared to the simulation environment because of other environmental factors.

Second, we displayed the average delay registered for MAC and ACK delays, Fig. 8. The results for MAC and...
ACK delay which is shown in the are same throughout 2000 consecutive evaluation. What we noticed is that all the delay types are interrelated and have direct influence on each other.

Figure 5 shows the unconditional delays registered in three different MNs during simulation analysis, the once in green color. As seen in the figure, it happens in two most common layers, physical and MAC. Notification, channel rendezvous, and inter-layer delay are some of the main reasons for such kind of delays. Even it is an unconditional delay the AMTL takes into account all classes of delays including these once.

Considering the dynamic changes in all types of delays, the proposed scheme consistently performs high measurement accuracy for a different number of MNs.

6. Conclusion

These days WSN researches are about spectrum-time-power (cognitive radio) and the number of MNs supported. However, it is essential to know what is the average minimum limit to use the techniques that these technologies offer. If we are below the minimum limit baseline and try to use any methods, improvements can’t be expected in our operating environment. So, knowing the AMTL will help anyone interested in designing any WSN applications especially for those interested in cognitive radio based WSN.

In case the reader is interested to know the total AMTL for his/her environment, the only thing he/she has to do is add up all the delays; queue, service, MAC, and ACK delays, together. Also, the reader should understand that the algorithm used and test circumstances remain the significant impact factors in such experiment, which are not part of the objective of this study. Regarding the channel congestion for IEEE 802.15.4 standard, it is an open problem for future study.

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Conflicts of Interest

The authors declared no potential conflicts of interest with
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