Analytical Framework for Throughput Enhancement in BLE Extended Advertising with Packet Chaining

Lalit Kumar Baghel, Gaoyang Shan, Eiman Kanjo, Byeong-Hee Roh

***Abstract*—Bluetooth Low Energy (BLE) 5.x introduced extended advertising with packet chaining for high-throughput BLE-based IoT applications. However, achieving maximal throughput in BLE largely depends on the selection of transmission parameters, such as packet size and the number of chained packets. Therefore, determining the optimal packet size and the number of chained packets is crucial. However, this task is challenging due to the nonlinearity of the problem. To date, none of the existing works have focused on determining the optimal values for these parameters. To address the aforementioned bottlenecks, we first develop a comprehensive analytical framework to model throughput. Based on this framework, we derive simplified closed-form analytical expressions to choose the transmission parameters optimally, ensuring maximal throughput. Additionally, we develop an algorithm that autonomously optimizes transmission parameters based on network configuration. Analytical results demonstrate that the proposed framework significantly improves throughput compared to conventional approaches. The accuracy of our analytical model is validated through simulations, demonstrating strong agreement with the analytical results.**

***Index Terms*—Bluetooth low energy (BLE), Extended advertising with packet chaining, Internet of things (IoT), throughput.**

I. Introduction

Bluetooth Low Energy (BLE) is a promising communication technology for IoT applications due to its low power consumption, cost-effectiveness, and wide adoption in devices like smartphones, smartwatches, and BLE beacons [1]. BLE enables short-to-medium-range communication, secure data transmission, and scalability, making it ideal for IoT use cases such as real-time location [2], healthcare [3], industrial IoT (IIoT) [4], etc.

BLE operates primarily in two modes: connection-oriented and connectionless [5]. The connectionless mode is particularly advantageous for IoT applications with a large number of BLE devices, as it provides lower energy consumption and enhanced scalability when compared to the connection-oriented mode. This mode is further divided into two sub-modes: legacy advertising and extended advertising [5].

BLE legacy advertising uses three primary advertising channels (37, 38, and 39) for data transmission, which limits scalability as the number of BLE devices grows. Additionally, this mode can transmit a maximum of 31 bytes per packet, resulting in limited throughput. These factors are critical for BLE-based IoT applications with a large number of BLE devices requiring higher throughput.

To address these limitations, the BLE Special Interest Group (SIG) introduced BLE extended advertising, which leverages 37 secondary advertising channels for data transmission while reserving the 3 primary channels for header transmission. This mode enables up to 255 bytes per packet, improving scalability and throughput to a certain extent [6]. However, despite these advancements, the throughput demands of certain BLE-based IoT applications may still remain unmet. To further enhance throughput, BLE SIG introduced packet chaining, which allows transmission of up to 1650 bytes of data [5]. This represents a substantial increase in throughput compared to both BLE legacy advertising and standard BLE extended advertising. Hence, the mode can meet the high throughput requirements of BLE-based IoT applications with a large number of devices.

Achieving maximal throughput in BLE-based IoT applications, particularly when using BLE extended advertising with packet chaining, is largely influenced by transmission parameters such as packet size, number of chained packets, number of advertisers, and advertising interval. Since the number of advertisers and advertising interval are often fixed due to application constraints, packet size and number of chained packets have a more direct and tunable impact on performance. Increasing packet size increases airtime, thereby raising the likelihood of collisions and reducing throughput. Conversely, very small packet sizes increase the number of required packets to transmit the same amount of data, resulting in longer overall transmission time and reduced throughput [6]. Therefore, an optimal packet size exists that maximizes throughput. Likewise, when the number of chained packets is too large, the packets become overpopulated, leading to extensive collisions [7], which in turn decreases throughput. On the other hand, a smaller number of chained packets requires more time for overall data transmission, which also negatively impacts throughput. Therefore, an optimal number of chained packets exists that maximizes throughput. Hence, determining the optimal packet size and the optimal number of chained packets is crucial for achieving maximal throughput.

Existing studies have primarily focused on BLE legacy advertising or BLE extended advertising, offering performance models to analyze discovery latency, data reception latency, and transmission rates. For instance, the authors in [8] and [9] analyzed and modeled discovery latency, proposing mathematical solutions to minimize discovery delays in both BLE legacy and extended advertising modes. Additionally, researchers in [10] and [4] developed analytical frameworks aimed at

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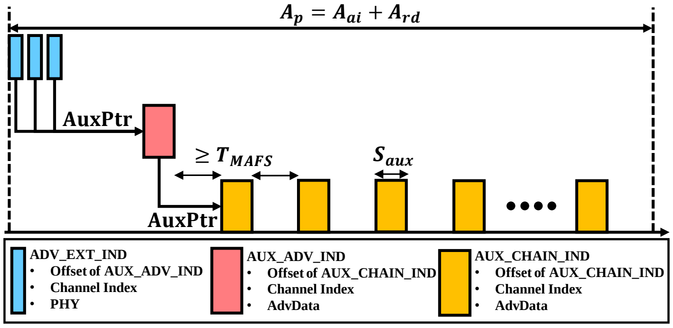


Fig. 1: BLE extended advertising with packet chaining.

reducing latency in BLE legacy and extended advertising, respectively. Furthermore, the authors in [6] proposed performance models to analyze transmission rates and provide optimal parameter settings for maximizing data transmission rates. However, to the best of the author's knowledge, none of the existing works have focused on optimizing transmission parameters, particularly packet size and number of chained packets, in BLE extended advertising with packet chaining to achieve maximal throughput, especially in BLE-based IoT applications with a large number of BLE devices. One notable study in [7] conducted an experimental investigation of BLE extended advertising and packet chaining, focusing on packet loss and energy efficiency. However, this study does not provide any insights into how transmission parameters can be optimally set to enhance overall performance.

To address the aforementioned issues, this letter provides simplified closed-form analytical expressions for optimally selecting transmission parameters to ensure maximal throughput. The main contributions of this work are summarized as follows:

- We develop an analytical framework to model throughput in BLE extended advertising with packet chaining, specifically focusing on IoT applications with a large number of BLE devices that require higher throughput.
- We derive simplified closed-form analytical expressions to optimally configure key transmission parameters, such as packet size and the number of chained packets, ensuring maximal throughput.
- We propose an algorithm that autonomously optimizes transmission parameters based on network configuration while ensuring maximum throughput.
- We validate the proposed analytical framework through simulations, which demonstrate strong alignment with the analytical results, confirming the accuracy and effectiveness of the framework.

II. System Model

This section introduces the system model for a BLE-based IoT application using BLE extended advertising with packet chaining, requiring higher throughput. BLE extended advertising with packet chaining is a two-step process. First, a packet called `ADV_EXT_IND` is transmitted on the primary advertising channels. This packet includes an auxiliary pointer field (`AuxPtr`) that specifies the start time and the index of the secondary advertising channel for the `AUX_ADV_IND` packet. The `AUX_ADV_IND` packet carries the initial portion of the payload. If the payload exceeds the 255 byte limit of a single packet, it is fragmented across up to K additional packets, each denoted as `AUX_CHAIN_IND`, allowing the total payload size to reach up to 1650 bytes. The `AUX_ADV_IND` and `AUX_CHAIN_IND` packets are transmitted on secondary advertising channels, which the controller randomly selects from the $M = 37$ available secondary advertising channels. The overall advertising process is illustrated in Fig. 1. BLE advertising operates without any coordination among advertisers, transmitting randomly within the advertising window; thus, even when $N < M$, collisions may occur due to overlapping transmissions. In this paper, we consider a system with N advertisers, where one is selected as the target advertiser. Our analysis focuses on optimizing the performance from the perspective of the target advertiser. The probability that an `ADV_EXT_IND` packet from the target advertiser collides with a packet from any other advertiser is $2S_{ext}/RA_p$ [10]–[12]. A transmission is successful if no collision occurs with any of the $(N-1)$ other advertisers. The success probability is thus given by:

TABLE I: Summary of notations.

Notation	Description
S_{ext}	`ADV_EXT_IND` packet size
S_{ovr}	`AUX_ADV_IND`/`AUX_CHAIN_IND` packet overhead
S_{aux}	`AUX_ADV_IND`/`AUX_CHAIN_IND` packet size
M, K	Number of secondary advertising channels and chained packets
R, N, A_p	PHY rate, number of advertisers, advertising period
C	Average collision probability considering all possible scenarios when K chained packets of an advertiser overlap with other
P_{se}	Success probability of `ADV_EXT_IND` packet
$P_{sa}, P_{sa}^{'}$	Success probability with and without packet chaining
P_s	Overall success probability
Δ	Symbol representing $\sqrt[N-1]{P_{sa}}$
T_{pc}	Throughput with packet chaining

$$P_{se} = \left[1 - \frac{2S_{ext}}{RA_p}\right]^{N-1} \tag{1}$$

Similarly, the success probability of single auxiliary `AUX_ADV_IND` packet $P_{sa}^{'}$ can be obtained as:

$$P_{sa}^{'} = \left[1 - \frac{2(S_{aux} + S_{ovr})}{RMA_p}\right]^{N-1} \tag{2}$$

Now, in the case of extended advertising with packet chaining, a collision with any of the packets in the chain is considered a data failure. Hence, none of the packets, including the `AUX_ADV_IND` and `AUX_CHAIN_IND` packets, must not collide with the transmissions from other BLE devices. The `AUX_ADV_IND` and each `AUX_CHAIN_IND` packet are transmitted on independently and randomly selected secondary advertising channels from the $M = 37$ available channels, resulting in a channel reuse probability of approximately $1/M$. Hence, the collision probability when only one chained packet collides is given by: $[(2(S_{aux} + S_{ovr}))/(RA_p)] \times [(1/M)]$. Similarly, when two chained packets collide, the collision probability is: $[(2(S_{aux}+S_{ovr}))/(RA_p)] \times [(1-(1-(1/M)))^2]$. When K chained packets collides, the collision probability becomes: $[(2(S_{aux} + S_{ovr}))/(RA_p)] \times [(1-(1-$

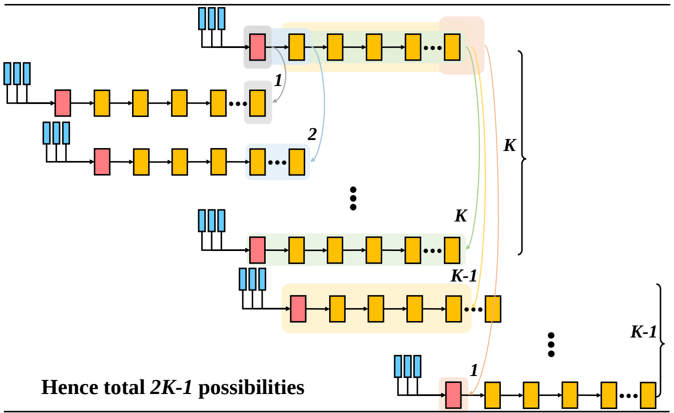


Fig. 2: Illustration of different collision scenarios in BLE extended advertising with packet chaining.

$(1/M)))^K]$. There can be various collision scenarios involving chained packets. For instance, the last packet of a BLE device may collide with the first packet of the reference BLE device. Similarly, the last two packets from a BLE device may collide with the first two packets from the reference BLE device, and so on, up to K packets from the BLE device overlapping with K packets of the reference BLE device. Furthermore, the last $K-1$ packets from a BLE device may overlap with the first $K-1$ packets of the reference BLE device, and so forth. Thus, there can be a total of $2K-1$ possible collision scenarios, as shown in Fig. 2. Taking these overlaps into account, the success probability of chained auxiliary `AUX_ADV_IND` and `AUX_CHAIN_IND` packets from a BLE device when N advertisers transmit randomly during the advertising period can be derived as follows:

$$P_{sa} = \left[1 - \frac{2\left(S_{aux} + S_{ovr}\right)}{RA_p} C\right]^{N-1} = \Delta^{N-1} \tag{3}$$

where C is given by:

$$C = \sum_{i=1}^{K}\left[1 - \left(1 - \frac{1}{M}\right)^i\right] + \sum_{i=1}^{K-1}\left[1 - \left(1 - \frac{1}{M}\right)^i\right] \tag{4}$$

Here, C represents the average collision probability considering all possible scenarios when K chained packets of an advertiser overlap with the other advertiser.

The terms in the above equation follow a geometric progression series with finite terms. Therefore, using the sum of finite terms in a geometric series identity given by $a(1-r^n)/(1-r)$, where a is the first term and r is the common ratio, the term C can be simplified further as follows:

$$C = \left[2(K-M) + 1 + (2M-1)\left(1 - \frac{1}{M}\right)^K\right] \tag{5}$$

For a BLE extended advertising transmission with packet chaining to be successful, none of the packets should collide with transmissions from other advertisers. Since `ADV_EXT_IND`, `AUX_ADV_IND`, and `AUX_CHAIN_IND` are transmitted over independent channel sets, the overall success probability (P_s) is the product of the individual success probabilities.

$$P_s = P_{se}P_{sa} \tag{6}$$

We define throughput as the successful data transmission per unit time. Hence, the throughput can be written as:

$$T_{pc} = \frac{KS_{aux}P_s}{A_p} \tag{7}$$

where K is number of chained packets, S_{aux} is the size of user data in one packet, P_s is the overall success probability, A_p is the advertising period. This expression can be used to analyze the throughput in BLE extended advertising with packet chaining in a BLE-based IoT network where N devices can start transmission randomly anytime in the given advertising period. All the notations used in this paper are summarized in Table I.

III. Optimization Framework

This section derives the expressions for optimal packet size and number of chained packets. First, the expression for the optimal packet size is derived, followed by the derivation of the optimal number of chained packets. Subsequently, an algorithm is introduced that autonomously optimizes the performance of the BLE-based IoT network. The optimal packet size of the auxiliary packet required to maximize throughput can be obtained by differentiating (7) with respect to S_{aux}, as shown below:

$$\frac{\partial T_{pc}}{\partial S_{aux}} = \frac{KP_{se}}{A_p}\left[\left(\frac{-2S_{aux}(N-1)C}{RA_p}\right)\Delta^{N-2} + \Delta^{N-1}\right] \tag{8}$$

Rearranging the above equation, we will get the following:

$$\frac{\partial T_{pc}}{\partial S_{aux}} = \frac{KP_{se}}{A_p}\Delta^{N-2} \times \left[\frac{-2S_{aux}(N-1)C}{RA_p} + 1 - \frac{2(S_{aux}+S_{ovr})C}{RA_p}\right] \tag{9}$$

To find the optimal value of S_{aux}, we set $\partial T_{pc}/\partial S_{aux} = 0$ and solve for the roots. Let $S_{aux}^{'}$ be the root that satisfies $\partial T_{pc}/\partial S_{aux} = 0$. The term $(KP_{se}/A_p)\Delta^{N-2}$ cannot be zero,. Therefore, by setting the expression $[(-2S_{aux}(N-1)C/RA_p) + 1 - (2(S_{aux}+S_{ovr})C/RA_p)] = 0$, we can solve for $S_{aux}^{'}$ as:

$$S_{aux}^{'} = \frac{RA_p - 2S_{ovr}(2(K-M)+1+(2M-1)\left(1-\frac{1}{M}\right)^K}{2N(2(K-M)+1+(2M-1)\left(1-\frac{1}{M}\right)^K} \tag{10}$$

Since $R = 1Mbps$, $M = 37$, $N \geq 2$, $S_{ovr} = 11bytes$ [5], hence, $RA_p >> 2S_{ovr}(2(K-M)+1+(2M-1)\left(1-\frac{1}{M}\right)^K$, thus (10) can be approximated as:

$$S_{aux}^{'} = \left[\frac{RA_p}{2N(2(K-M)+1+(2M-1)\left(1-\frac{1}{M}\right)^K}\right] \tag{11}$$

The shape of T_{pc} depends on the sign of $\partial T_{pc}/\partial S_{aux}$. Specifically, in the region where $\partial T_{pc}/\partial S_{aux}$ has a positive value, T_{pc} increases as S_{aux} increases, and vice versa. From (7), we can obtain the following relationship: $\partial T_{pc}/\partial S_{aux} > 0$ for $S_{aux} < S_{aux}^{opt}$ and $\partial T_{pc}/\partial S_{aux} < 0$ for $S_{aux} > S_{aux}^{opt}$. This means that T_{pc} has maxima at $S_{aux}^{'}$. Hence the expression for optimal S_{aux} (S_{aux}^{opt}) can be written as:

$$S_{aux}^{opt} = \left[\frac{RA_p}{2N(2(K-M)+1+(2M-1)\left(1-\frac{1}{M}\right)^K}\right] \tag{12}$$

This closed-form, simplified analytical expression can be used to find S_{aux}^{opt} that maximizes the T_{pc}.

Similarly, we differentiate (7) with respect to K to obtain K^{opt} expression that maximizes T_{pc}. The K^{opt} expression can be determined as:

$$\frac{\partial T_{pc}}{\partial K} = \beta_1 \Delta^{N-2}(\beta_2 + \Delta) \tag{13}$$

where β_1 and β_2 are as follows:

$$\begin{aligned}\beta_1 = \frac{S_{aux}P_{se}}{A_p}, \beta_2 = K(N-1)\left(\frac{-2(S_{aux}+S_{ovr})}{RA_p}\right) \\ \times \left[2 + (2M-1)\left(1-\frac{1}{m}\right)^K \ln\left(1-\frac{1}{M}\right)\right]\end{aligned} \tag{14}$$

To find optimal K, set $\partial T_{pc}/\partial K = 0$, and then solve for the roots. Let $K^{'}$ be the value of K that satisfies $\partial T_{pc}/\partial K = 0$. The term $\beta_1 \Delta^{N-2}$ can not be zero. Hence equating the term $\beta_2 + \Delta$ to 0, we will obtain the following expression:

$$\begin{aligned}\Bigg[2NK^{'} - 2M + 1 + (2M-1)\left(1-\frac{1}{M}\right)^{K^{'}} \\ \times \left(1 + K^{'}(N-1)\ln\left(1-\frac{1}{M}\right)\right)\Bigg] = \frac{RA_p}{2(S_{aux}+S_{ovr})}\end{aligned} \tag{15}$$

The shape of T_{pc} depends on the sign of $\partial T_{pc}/\partial K$. Specifically, in the region where $\partial T_{pc}/\partial K$ has a positive value, T_{pc} increases as K increases, and vice versa. From (7), we can obtain the following relationship: $\partial T_{pc}/\partial K > 0$ for $K < K^{opt}$ and $\partial T_{pc}/\partial K < 0$ for $K > K^{opt}$. This means that T_{pc} has maxima at K^{opt}. Hence, the K^{opt} expression can be written as:

$$\begin{aligned}\Bigg[2NK^{opt} - 2M + 1 + (2M-1)\left(1-\frac{1}{M}\right)^{K^{opt}} \\ \times \left(1 + K^{opt}(N-1)\ln\left(1-\frac{1}{M}\right)\right)\Bigg] = \frac{RA_p}{2(S_{aux}+S_{ovr})}\end{aligned} \tag{16}$$

This closed-form, simplified analytical expression can be used to find K^{opt} that maximizes the T_{pc}. Since the K^{opt} expression involves logarithmic and exponential terms, it can not be solved directly. Hence, the numerical method known as the bisection method is proposed to obtain the K^{opt} value.

The simplified closed-form analytical expressions obtained in (12) and (16) are fed to the Algorithm 1 running in the BLE gateway, which optimizes transmission parameters based on network configuration while ensuring maximum throughput.

Algorithm 1 Autonomous Network Management

```
Input: N, R, A_p, M, S_ovr
Output: S_aux^opt, K^opt
Step 1: Compute optimal parameters
Set K = 1 and compute S_aux^opt using (12).
if S_aux^opt < 254 then
    Set S_aux = S_aux^opt and K^opt = 1.
else
    Compute K^opt from (16) using bisection method.
    Set S_aux^opt = 254 bytes and K^opt as the optimal solution.
end if
Step 2: Broadcast parameters and start transmission
The BLE gateway broadcasts S_aux^opt, K^opt to BLE devices;
BLE devices receive these settings and start transmission.
Step 3: Monitor and adapt to changes
while network is operational do
    if changes in N, R, A_p, M, S_ovr then
        Recompute S_aux^opt and K^opt as shown in Step 1.
        Broadcast updates to BLE devices.
    else
        Maintain transmission at S_aux^opt and K^opt.
    end if
end while
```

IV. Results and Discussion

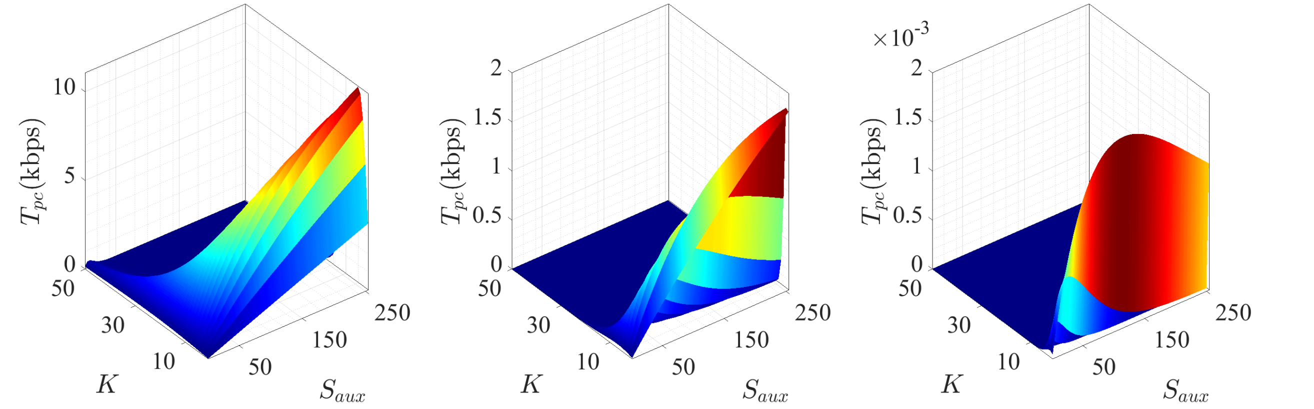
This section presents the analytical, simulation, and comparison results of the proposed approach. Specifically, it first provides the analytical results, followed by simulation results obtained from the BLE simulator [13] developed using Riverbed Modeler (formerly OPNET) [14] to validate the proposed framework. Each simulation scenario was executed 500 times, and average values were reported to ensure result consistency. Finally, it compares the performance of the proposed approach (PA) with the conventional approach (CA). The results confirm that PA consistently achieves superior throughput than CA, primarily due to its use of optimized parameters. The simulations and analytical evaluations were conducted using the following settings: $S_{ext} = 18$ bytes, $S_{aux} =$ 1–254 bytes, $S_{ovr} = 11$ bytes, $R = 1$ Mbps, $M = 37$, $K =$ 1–50, $N =$ 100–10,000, and $A_p = 500$ ms.

A. Impact of S_{aux} and K on T_{pc}

Fig. 3 shows the variation of T_{pc} with S_{aux} and K for different values of N. From Fig. 3, it can be observed that there exist optimal values of S_{aux} and K that maximize the T_{pc}. These values can be obtained easily with the simplified closed-form expressions obtained in (12) and (16), respectively. In particular from Fig. 3a, it can be observed that S_{aux}=254 bytes and K=5 achieves maximal T_{pc}, similarly S_{aux}=254 bytes and K=2, and S_{aux}=115 bytes and K=1, achieves maximal T_{pc} for N=1000, N=10000 respectively, as shown in Fig. 3b and Fig. 3c. It is because, for smaller N (N=100, N=1000), the collisions are less than for larger N (N=10000). Hence, larger N supports only 1 packet in the chain, and that to with a smaller packet size, whereas the smaller N (N=100, N=1000) supports 5 and 2 packets in the chain with full packet size.

B. Comparison of the PA with CA

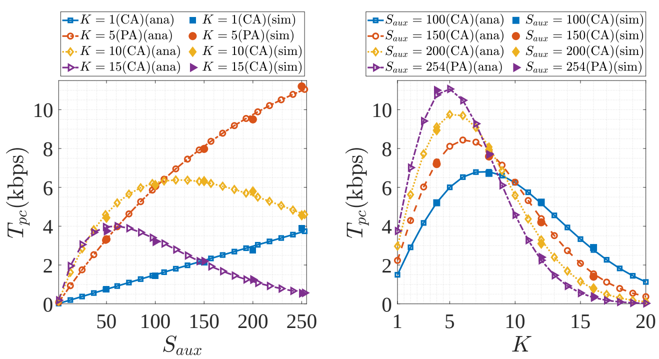
Fig. 4 shows the comparison results of the proposed approach (PA) with the conventional approach (CA). From Fig. 4, it can be observed that the proposed approach achieves a superior throughput than the conventional approach. It is because, in the PA, the parameters S_{aux} and K are optimally selected using closed-form expressions derived in Equations (12) and (16), leading to improved throughput and more efficient BLE resource utilization. In contrast, the baseline CA



(a) (b) (c)

Fig. 3: Variation of T_{pc} with respect to K and S_{aux} for different values of N: (a) N = 100, (b) N = 1000, (c) N = 10000. The results indicate that as N increases, both K and T_{pc} decrease.

selects these parameters randomly, which results in suboptimal performance. Also, it can be observed that the analytical results align closely with the simulation results, with a very small deviation that can be ignored.



(a) (b)

Fig. 4: (a) Variation of T_{pc} with S_{aux} for different values of K, (b) Variation of T_{pc} with K for different values of S_{aux}. The results indicate that for a given N, there exists an optimal combination of K and S_{aux} that leads to higher throughput.

V. Conclusion

This letter presents an analytical framework for deriving optimal parameter settings in BLE extended advertising mode with packet chaining, aiming to maximize throughput. In particular, we first develop an analytical framework to model the throughput of BLE extended advertising with packet chaining. Building on this model, we derive simplified closed-form analytical expressions to optimally configure key transmission parameters, such as the size of the `AUX_ADV_IND` and `AUX_CHAIN_IND` packets, as well as the number of chained packets. Additionally, based on these expressions, we develop an algorithm that autonomously optimizes the key transmission parameters based on network configuration while ensuring maximal throughput. Analytical results demonstrate that the proposed framework significantly improves the throughput compared to conventional approaches, making it well-suited for BLE-based IoT applications where high throughput is essential.

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