A Comparison of Radio Power Consumption of True Wireless Earbuds

Thomas Girardier, Florian Denis and Antoine Soulier

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Thomas Girardier, *CTO* **and Florian Denis,** *R&D Engineer* **and Antoine Soulier,** *R&D Engineer*
(thomas@tempow.com) (florian@tempow.com) (antoine@tempow.com)

Tempow, Paris, France

This study models and compares audio streaming radio power consumptions of Bluetooth true wireless earbuds technologies based on a transmitting and receiving durations. Four architectures are reviewed: Bluetooth forwarding, NFMI forwarding, Bluetooth eavesdropping, and Bluetooth dual stream. Three audio configurations are detailed.

0 INTRODUCTION

True wireless earbuds refer to earbuds that have neither cords or wires between them nor to an audio source. They first appeared on the market in mid-2016 and since became one of the trendiest products in the audio industry. All true wireless earbuds use the Bluetooth protocol [1] and the Advanced Audio Distribution Profile (A2DP) [2] to connect to an audio source (smartphones, computers, *etc.*) but different approaches have been developed to allow both earpieces to get the audio data.

One of the first architecture designed to solve this issue is called *Bluetooth forwarding*: in its *basic* version, one earpiece receives a stereo stream from the audio source on a first Bluetooth link and then retransmits the same stream to the other earpiece on a second Bluetooth link. An *optimized* version of this architecture consists in retransmitting only the channel corresponding to the second earpiece.

As the use of Bluetooth radio waves is not suited for data transmission through the head (which effectively blocks 2.4 GHz wavelengths), the *Near Field Magnetic Induction (NFMI) forwarding* has been developed: one earpiece receives a stereo stream from the audio source through a Bluetooth link and retransmits the corresponding channel to the other earpiece using an NFMI link. Both those architectures are illustrated in Figure 1.

Recently two other architectures have been developed to avoid having a forwarding link between the two earpieces. The first one is *Bluetooth eavesdropping*: like the forwarding techniques, one earpiece is connected to the audio source and receives a stereo stream. It also shares with the other earpiece the information needed for it to sniff the established Bluetooth link and receive the same stereo stream, unbeknownst to the source.

The second one is called *Bluetooth dual stream*: unlike the other solutions, the two earpieces are connected to the audio source using two separate Bluetooth links, and each receives a mono stream. Both those architectures are illustrated in Figure 2.

This study models and compares the efficiency of those solutions in term of radio power consumption.

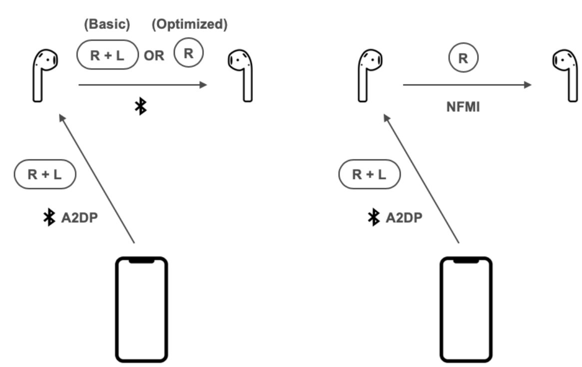

Fig. 1. Forwarding using Bluetooth (left) or NFMI (right).

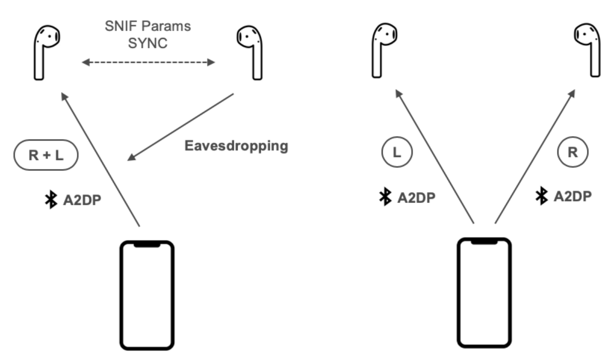

Fig. 2. Bluetooth Eavesdropping (left) and Dual Stream (right) architectures.

1 MODELING BLUETOOTH RADIO POWER CONSUMPTION

The power consumption of a Bluetooth radio is linked to the time it spends in Idle, Receiving (RX) and Transmitting (TX) modes. A Bluetooth piconet physical channel is divided into time slots, each 625 µs in length [1]. The master transmission always starts at even numbered time slots and the slave transmission always starts at odd numbered time slots. Some packets can cover more than a single slot so master transmission may continue in odd numbered slots and slave transmission may continue in even numbered slots. A typical Bluetooth radio operation is illustrated in Figure 3.

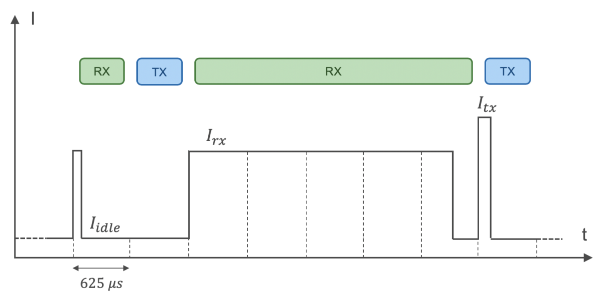

Fig. 3. Typical modes of operation of a Bluetooth chip.

Neglecting transient performances, the average power of a Bluetooth radio on a d_{total} duration can be modeled using Equation 1.

$$P_{avg,BT} = \frac{d_{idle}P_{idle} + d_{rx}P_{rx} + d_{tx}P_{tx}}{d_{total}} \tag{1}$$

Where d_{idle}, d_{rx} and d_{tx} are respectively the Idle, RX and TX durations. Assuming that voltage is constant during all the operation modes of the chip:

$$P_{avg,BT} = V \cdot \frac{d_{idle}I_{idle} + d_{rx}I_{rx} + d_{tx}I_{tx}}{d_{total}} \tag{2}$$

In what follows, we will consider a total duration of one second.
To compute the overall radio power consumption, the average power of the NFMI radio needs to be added to the Bluetooth average power.

2 CALCULATING IDLE, RX AND TX DURATIONS

To compute the average Bluetooth power, Idle, RX and TX durations must be calculated. They depend on three parameters:

- The number of active and passive cycles.
- The Bluetooth packets.
- The architecture of the solution.

2.1 Active and Passive Cycles

An active cycle consists of the reception of an audio packet by an earpiece, the transmission of an acknowledgment, and, if applicable, the retransmission to the other earpiece. An active cycle can take a variable number of Bluetooth slots depending on the chosen architecture. A passive cycle is a two slots cycle which consists of one RX slot where the earpiece checks whether a data is transmitted on the physical channel (meaning listening to the sync word) and one TX slot where the earpiece stays in Idle state. There is no transmission in a passive cycle. The RX, TX and Idle durations can be calculated using Equations 3, 4 and 5.

$$d_{rx} = n_{active/s} \cdot d_{rx,active} + n_{passive/s} \cdot d_{rx,passive} \tag{3}$$

$$d_{tx} = n_{active/s} \cdot d_{tx,active} \tag{4}$$

$$d_{idle} = 1s - d_{rx} - d_{tx} \tag{5}$$

Where $n_{active/s}$, $n_{passive/s}$ are respectively the number of active and passive cycle in one second, $d_{rx,active}$, $d_{tx,active}$ are respectively the duration in RX mode and TX mode in an active cycle and $d_{rx,passive}$ the duration in RX mode in a passive cycle. There are 1600 Bluetooth slots in one second, so if each active cycle takes $n_{slots/passive}$ slots:

$$n_{passive/s} = \frac{1600 - n_{active/s} \cdot n_{slots/active}}{2} \tag{6}$$

2.2 Bluetooth Packets

To determine RX and TX durations during active and passive cycles, two types of Bluetooth packet must be considered.

2.2.1 2-DH5 Packets

We make the assumption that audio data are sent into 2-DH5 ACL Bluetooth packets. This is the default packet type in Android and on several platforms. 2-DH5 packets are Enhanced Data Rate (EDR) packets that occupy five time slots and are composed of two parts.
The first part consists of a 72 bits access code (including 4 bits preamble, 64 bits sync word and 4 bits trailer) which is used to identify all packets exchanged on a Bluetooth piconet physical channel and a 58 bits header which notably includes the *LT_ADDR* of the receiver and the packet type. This first part is modulated using GFSK (1 Mbit/s).
The second part consists of a 11 µs synchronization sequence, a payload with up to 683 octets (which includes a 2 octets header and a 16 bits CRC) and a 2 symbols trailer. This part is modulated using π/4 - DQPSK (2 Mbit/s). It is separated from the first part by a 5 µs guard time.
The total duration of a 2-DH5 packet is thus:

$$d_{2-DH5,true} = 148 + \frac{length_{audio/packet}}{2} \text{ µs} \tag{7}$$

Where $length_{audio/packet}$ is the length in bits of the audio data contained in a single packet.
When a device in the piconet receives a 2-DH5 packet which is not addressed to it (different *LT_ADDR* in the header), it ignores the rest of the packet and goes back to Idle mode. Only the access code and the header are read. The duration of a reception of a "false" 2-DH5 packet is thus:

$$d_{2-DH5,false} = 126 \text{ µs} \tag{8}$$

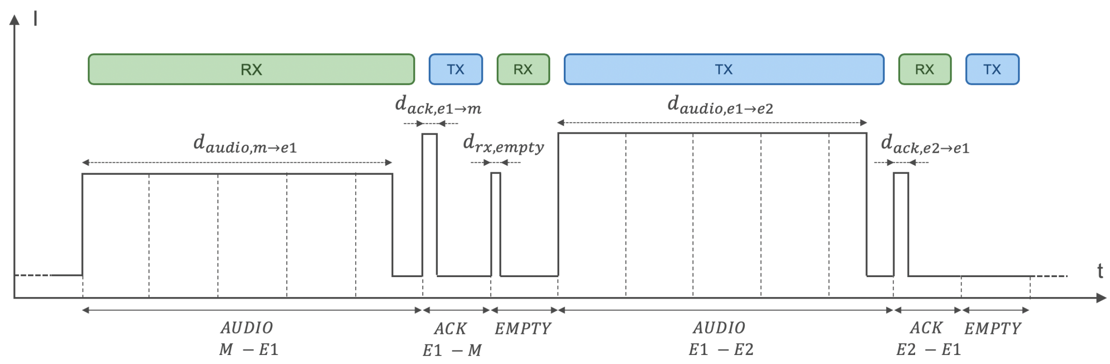

Fig. 4. Active cycle of earpiece 1 (retransmitting) for the Basic Bluetooth forwarding architecture.

When no sync word is detected at the start of the reception slot, the device goes back to Idle mode directly. The duration in receiving mode in an "empty" RX slot is thus:

$$d_{rx,empty} = 68\ \mu s \tag{9}$$

2.2.2 NULL Packets

NULL packets have no payload and consist of the channel access code and packet header only. Their total length is fixed at 126 bits. NULL packets are used for acknowledgment of the previous transmission. An acknowledgment always happens on the TX slot following the reception of the acknowledged packet. Their duration is:

$$d_{ack} = 126\ \mu s$$

2.3 Basic Bluetooth forwarding

For the Basic Bluetooth forwarding architecture, we need to distinguish between the radio behavior of earpiece 1, which retransmits the audio data, and the radio behavior of earpiece 2, which only receives audio data. An active cycle of earpiece 1 is illustrated in Figure 4. It takes 14 time slots including:

- 5 RX slots to receive a 2-DH5 audio packet from the audio source (master).
- 1 TX slot to acknowledge it.
- 1 RX slot where the chip only listens to the sync word (because this slot cannot be used for retransmission).
- 5 TX slots to retransmit the audio data to earpiece 2.
- 1 RX slot to receive the earpiece 2 acknowledgment.
- 1 TX slot where the chip stays in Idle state.

RX and TX durations can be calculated with equations 7 and 8.

$$\begin{aligned} d_{rx,active} &= d_{audio,m\to e1} + d_{rx,empty} + d_{ack,e2\to e1} \\ &= d_{2-DH5,true} + d_{rx,empty} + d_{ack} \end{aligned} \tag{10}$$

$$\begin{aligned} d_{tx,active} &= d_{audio,e1\to e2} + d_{ack,e1\to m} \\ &= d_{2-DH5,true} + d_{ack} \end{aligned} \tag{11}$$

An active cycle of earpiece 2 is illustrated in Figure 5. It takes 6 time slots including 5 RX slots to receive the audio data from earpiece 1 and 1 TX slot to acknowledge it. RX and TX durations are thus:

$$d_{rx,active} = d_{audio,e1\to e2} = d_{2-DH5,true} \tag{12}$$

$$d_{tx,active} = d_{ack,e2\to e1} = d_{ack} \tag{13}$$

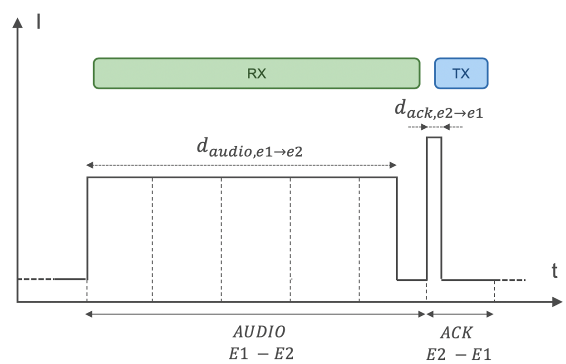

Fig. 5. Active cycle of earpiece 2 in Bluetooth forwarding.

2.4 Optimized Bluetooth forwarding

For the Optimized Bluetooth forwarding architecture, we also need to distinguish the radio behavior of earpiece 1 and earpiece 2. Compared to the Basic Bluetooth Forwarding, retransmissions do not always happen on earpiece 1 because we need more multiple 2-DH5 stereo packets to fill a 2-DH5 mono packet. We thus must consider two types of active cycles:

- An active cycle when a retransmission happens. It is identical to earpiece 1 active cycle in the Basic Bluetooth Forwarding.
- An active cycle when there is no retransmission. It is similar to earpiece 2 active cycle in the Basic Bluetooth Forwarding.

Equations 3, 4 and 6 must thus be updated in the following way. For earpiece 1 (retransmitting):

$$\begin{aligned} d_{rx} = {} & n_{active\_no\_ret/s} \cdot d_{rx,active\_no\_ret} \\ & + n_{active\_ret/s} \cdot d_{rx,active\_ret} + n_{passive/s} \cdot d_{rx,passive} \end{aligned}$$

$$d_{tx} = n_{active\_no\_ret/s} \cdot d_{tx\_no\_ret,active}$$

$$+n_{active\_ret/s} \cdot d_{tx\_ret,active}$$

With:

$$d_{rx,active\_ret} = d_{2-DH5,true} + d_{rx,empty} + d_{ack} \quad (14)$$

$$d_{tx,active\_ret} = d_{2-DH5,true} + d_{ack} \quad (15)$$

$$d_{rx,active\_no\_ret} = d_{2-DH5,true} \quad (16)$$

$$d_{tx,active\_no\_ret} = d_{ack} \quad (17)$$

With the number of passive cycles equal to:

$$n_{passive/s} = \frac{1}{2} \cdot (1600 - n_{active\_no\_ret/s} \cdot n_{slots/active\_no\_ret} - n_{active\_ret/s} \cdot n_{slots/active\_ret})$$

For earpiece 2:

$$d_{rx} = n_{active\_ret/s} \cdot d_{rx,active\_ret} + n_{passive/s} \cdot d_{rx,passive}$$

$$d_{tx} = n_{active\_ret/s} \cdot d_{tx,active\_ret}$$

With:

$$d_{rx,active\_ret} = d_{2-DH5,true} \quad (18)$$

$$d_{tx,active\_ret} = d_{ack} \quad (19)$$

With the number of passive cycles equal to:

$$n_{passive/s} = \frac{1600 - n_{active\_ret/s} \cdot n_{slots/active\_ret}}{2}$$

2.5 NFMI forwarding

For the NFMI forwarding solution, we also need to distinguish the radio behavior of earpiece 1 and earpiece 2. The Bluetooth radio of Earpiece 2 is not used during audio streaming as it is forwarded using NFMI. An active cycle of earpiece 1 is illustrated in Figure 6.

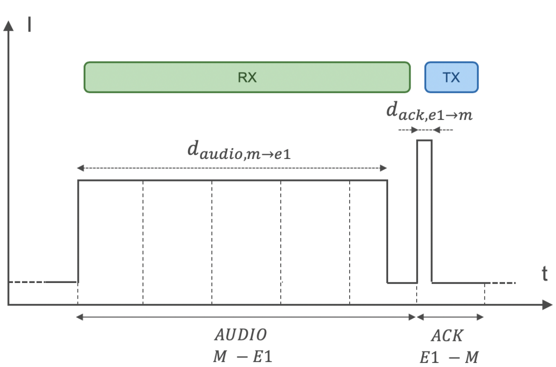

Fig. 6. Active cycle of earpiece 1 (retransmitting) for the NFMI forwarding solution.

An active cycle takes 6 slots: 5 RX slots to receive a 2-DH5 audio packet and 1 TX slot to acknowledge it. RX and TX durations are thus:

$$d_{rx,active} = d_{audio,m\to e1} = d_{2-DH5,true} \quad (20)$$

$$d_{tx,active} = d_{ack,e1\to m} = d_{ack} \quad (21)$$

2.6 Eavesdropping

One of the challenges of the eavesdropping architecture is the acknowledgment of the audio packets by the sniffing earpiece, which must be done to provide a reliable streaming experience. It is mandated by the Bluetooth standard that earpiece 1 must acknowledge on the TX slot which follows the reception of the audio data sent by the source. Because of that, it seems impossible for it to wait for the acknowledgment of earpiece 2.
However, because a 2-DH5 packet does not take the full 5 Bluetooth time slots, one (not standard-compliant) solution is to transmit/receive the acknowledgment during the remaining time. In this case, the active cycle of earpiece 1 is illustrated in Figure 7.

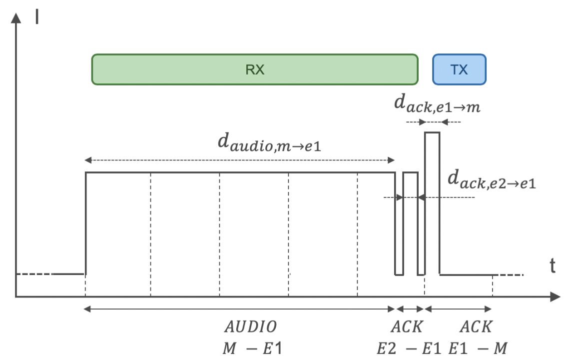

Fig. 7. Active cycle of earpiece 1 in the eavesdropping solution.

An active cycle takes 6 time slots including:

- 5 RX slots to receive a 2-DH5 audio packet from the audio source (master) and to receive the acknowledgment of earpiece 1 (not standardized).
- 1 TX slot to acknowledge the audio source of the success of the reception of both earpieces.

The RX and TX durations are thus:

$$d_{rx,active} = d_{audio,m\to e1} + d_{ack,e2\to e1} = d_{2-DH5,true} + d_{ack} \quad (22)$$

$$d_{tx,active} = d_{ack,e1\to m} = d_{ack} \quad (23)$$

An active cycle of earpiece 2 is illustrated in Figure 8.

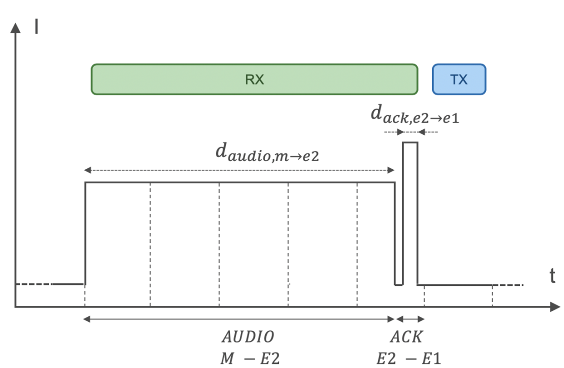

Fig. 8. Active cycle of earpiece 2 in the eavesdropping solution.

It takes 6 time slots including 5 RX slots to receive the sniffed audio data and to acknowledge earpiece 1 (not standardized) and 1 empty TX slot.

$$d_{rx,active} = d_{audio,m\rightarrow e1} = d_{2-DH5,true} \tag{24}$$

$$d_{tx,active} = d_{ack,e2\rightarrow e1} = d_{ack} \tag{25}$$

2.7 Dual stream

For the dual stream solution, both earpieces are in the same Bluetooth piconet and they receive their respective audio data in a time multiplexed way. Because packets in a same piconet have the same access code, packets sent to earpiece 1 are also received by earpiece 2 which ignores them after reading the header. Active cycle is identical on both earpieces and is illustrated in Figure 9. It takes 12 time slots including:

- 5 RX slots to receive a 2-DH5 audio packet from the audio source.
- 1 TX slot to acknowledge it.
- 5 RX slots where the audio source sent an audio packet to earpiece 2.
- 1 TX slot where the chip stays in Idle state.

Thus, RX and TX durations are defined by equations 26 and 27.

$$\begin{aligned} d_{rx,active} &= d_{audio,m\rightarrow e1} + d_{audio,m\rightarrow e2} \\ &= d_{2-DH5,true} + d_{2-DH5,false} \end{aligned} \tag{26}$$

$$d_{tx,active} = d_{ack,e1\rightarrow m} = d_{ack} \tag{27}$$

2.8 Retransmissions

Some Bluetooth packets may be corrupted during their transmission due to interferences or poor link quality and may impact the RX, TX and Idle durations. We will only consider corrupted audio packets (and not acknowledgment packets) and single retransmissions (the second transmission is always received). We will also consider that the corruption happens in the packet payload and not on the access code and header (which is a reasonable assumption since for audio packets, the payload is much longer than the access code and the header). In this case, a corrupted packet will be entirely received, and corruption will be detected using the CRC included in the payload.

In this way, an active cycle which includes the reception of a corrupted audio packet will take 6 more slots, including 5 RX slots and 1 empty TX slot. In the same manner, an active cycle which includes a transmission of an audio packet that is not acknowledged will take 6 more slots including 5 TX slots and 1 empty RX slot.

3 NUMBER OF ACTIVE CYCLES

The number of active cycles in one second depends on the amount of audio data that needs to be transmitted and also the audio configuration. The more data needs to be sent, the more active cycles there are.

We consider three different audio configurations using the following codecs: SBC 328 kbit/s (High Quality settings as defined in the A2DP specification [2]), AAC 256 kbit/s and LDAC 990 kbit/s. We always consider a 44100 Hz sample rate.

An audio packet payload includes an 8 octets Logical Link Control and Adaptation Protocol (L2CAP) header [1] and a 12 octets Audio and Video Distribution Transport Protocol (AVDTP) [3] header, which leaves 659 octets for the audio data.

Assuming that there is only an integer number of frames (that is, the basic unit can be decoded independently) in a packet, we can compute the number of audio packets per second sent by the audio source using the length of a frame in bytes and the frame rate (the number of frames per second), and thus the number of active cycles per second.

$$n_{active/s} = \frac{frame\_rate}{n\_frames/packet} = \frac{frame\_rate}{\left\lfloor \frac{659}{frame\_length} \right\rfloor} \tag{28}$$

Considering these parameters, the duration of a 2-DH5 packet is equal to:

$$d_{2-DH5,true} = 148 + \frac{frame\_rate \cdot frame\_length \cdot 8}{2}\ \mu s \tag{29}$$

Table 1 illustrates the values of the number of active cycles per second and the duration of a 2-DH5 packet in µs for different codecs and configurations.

Table 1. Active cycles and packet durations.

Codec	Configuration	Active Cycles	2-DH5 dur.
SBC	328 kbit/s Joint Stereo	68.906	2560
SBC	193 kbit/s Mono	38.281	2700
AAC	256 kbit/s Stereo	43.066	2896
AAC	128 kbit/s Mono	21.533	2896
LDAC	990 kbit/s Stereo	172.267	2896
LDAC	454.5 kbit/s Mono	86.133	2896

The number of active cycles in Basic Bluetooth forwarding, NFMI forwarding and eavesdropping is equal to the number of active cycles with a stereo configuration. The number of active cycles in Dual stream is equal to the number of active cycles with a mono configuration. The number of active cycles with retransmission and without retransmission in Optimized Bluetooth forwarding are respectively equal to the number of active cycles with a mono configuration and a stereo configuration.

4 RESULTS

Using the previous equations, we can compute the resulting TX, RX and Idle durations for the different solutions. Table 2 shows the results. Note that the LDAC 990 kbit/s configuration is not possible using the Bluetooth forwarding because it requires more time slots than available.

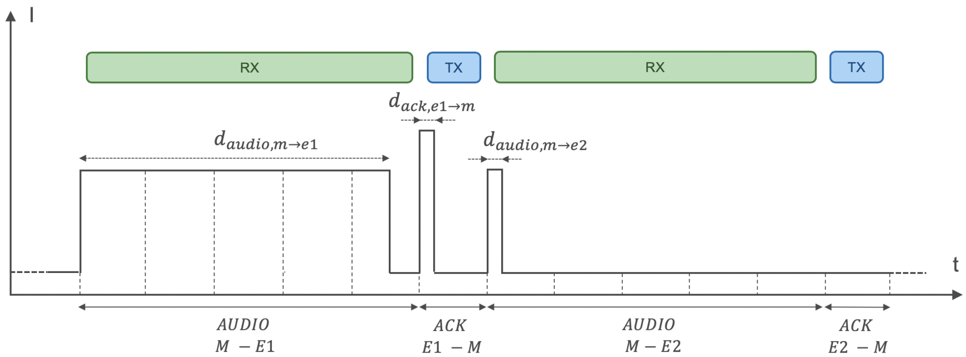

Fig. 9. Active cycle of the dual stream solution.

Table 2. Bluetooth RX and TX durations in milliseconds for the different configurations on a total period of one second.

Architecture	Codec	RX duration	TX duration
Basic Forw. BT 1	SBC	211.367	185.081
Basic Forw. BT 2	SBC	216.742	8.682
Basic Forw. BT 1	AAC	166.975	130.146
Basic Forw. BT 2	AAC	170.334	5.426
Basic Forw. BT 1	LDAC	Not possible	Not possible
Basic Forw. BT 2	LDAC	Not possible	Not possible
Optim. Forw. BT 1	SBC	213.757	112.041
Optim. Forw. BT 2	SBC	149.950	4.823
Optim. Forw. BT 1	AAC	168.655	67.786
Optim. Forw. BT 2	AAC	112.367	2.713
Optim. Forw. BT 1	LDAC	Not possible	Not possible
Optim. Forw. BT 2	LDAC	Not possible	Not possible
Forwarding NFMI 1	SBC	216.742	8.682
Forwarding NFMI 1	AAC	170.335	5.426
Forwarding NFMI 1	LDAC	518.139	21.705
Eavesdropping 1	SBC	225.425	8.682
Eavesdropping 2	SBC	216.742	8.682
Eavesdropping 1	AAC	175.761	5.426
Eavesdropping 2	AAC	170.335	5.426
Eavesdropping 1	LDAC	539.845	21.705
Eavesdropping 2	LDAC	518.139	21.705
Dual Stream 1/2	SBC	146.963	4.823
Dual Stream 1/2	AAC	110.688	2.713
Dual Stream 1/2	LDAC	279.551	10.853

To calculate the corresponding power consumptions, we use the electrical characteristics of a Cypress CYW20721 Bluetooth chip [4] and of a NXP NxH2281 NFMI radio [5].
The CYW20706 has a radio current consumption of 100 µA in Idle, 5.9 mA in EDR RX and 5.6 mA in EDR TX (0dBm) and is running at 3 V. The NxH2265 has an average power consumption of 3 mW during streaming.
Assuming that the roles of earpiece 1 and 2 can be reversed periodically to compensate the over consumption of one compared to the other, Table 3 shows the average power consumption per earpiece for each solution and audio configuration.
Supposing a retransmission ratio of 10%, which is a good average in practical use case, Table 4 shows the average power consumption per earpiece.

Table 3. Average radio power consumption for each solution and for each audio configuration without retransmission.

Architecture	Codec	Power Consumption (mW)
Basic Forw. BT	SBC	5.518
Basic Forw. BT	AAC	4.262
Basic Forw. BT	LDAC	Not possible
Optim. Forw. BT	SBC	4.317
Optim. Forw. BT	AAC	3.232
Optim. Forw. BT	LDAC	Not possible
Forwarding NFMI	SBC	5.014
Forwarding NFMI	AAC	4.602
Forwarding NFMI	LDAC	7.613
Eavesdropping	SBC	4.099
Eavesdropping	AAC	3.250
Eavesdropping	LDAC	9.406
Dual Stream	SBC	2.809
Dual Stream	AAC	2.174
Dual Stream	LDAC	5.101

5 CONCLUSION

The power consumption model shows that the Dual Stream architecture is the most efficient. Eavesdropping is the second best solution with a typical 47% increase of the radio power consumption compared to the Dual Stream architecture. Optimized Bluetooth forwarding achieves almost the same performances than the eavesdropping with a typical increase of 55%. The NFMI forwarding solution comes after with a typical increase of 74%. The Bluetooth forwarding is the worst architecture with a typical increase of 100%. These differences are accentuated when the number of retransmissions or the bitrate of the codec increase. Because the power consumption is much more important on the forwarding earpiece, a role switching mechanism is necessary to reduce the power consumption for both NFMI and Bluetooth Forwarding, which further complicates those solutions. The Eavesdropping and the Dual Stream solution do not need such mechanism as the power consumption is almost equally distributed on both earpieces.

We assumed than the radio is doing only the audio streaming, which is not the case in real solutions as they also require between-ear communications for the synchronization, remote controls and/or the pairing process. However, the impact of these communications on the radio power consumption is negligible compared to the impact of the streaming.

In a Bluetooth true wireless earpiece, the Bluetooth radio typically contributes to 25% of the overall power consumption (40% is for the hardware codec and 35% for the MCU and the decoding process). Using the Dual Stream architecture instead of the Bluetooth forwarding can correspond to a 26% increase of the overall battery life, providing one extra hour of streaming for a pair of earbuds with a 4h battery life.

Today, while the architecture is not directly perceived by the end user, it greatly impact the performances of the device, especially in term of power comsumption.

Table 4. Average radio power consumption for each solution and for each audio configuration with 10% retransmissions.

Architecture	Codec	Power Consumption (mW)
Basic Forw. BT	SBC	5.928
Basic Forw. BT	AAC	4.555
Basic Forw. BT	LDAC	Not possible
Optim. Forw. BT	SBC	4.613
Optim. Forw. BT	AAC	3.426
Optim. Forw. BT	LDAC	Not possible
Forwarding NFMI	SBC	5.148
Forwarding NFMI	AAC	4.698
Forwarding NFMI	LDAC	7.996
Eavesdropping	SBC	4.374
Eavesdropping	AAC	3.445
Eavesdropping	LDAC	10.189
Dual Stream	SBC	2.961
Dual Stream	AAC	2.266
Dual Stream	LDAC	5.473

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