A Comparison among Wi-Fi Direct, Classic Bluetooth, and Bluetooth Low Energy Discovery Procedures for Enabling Massive Machine Type Communications

Abel Rodriguez Medel and Jose M. Camara Brito
National Institute of Telecommunications INATEL, Santa Rita do Sapucai, MG, Brazil

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Abstract: The exponential growth of the Internet of Things (IoT) devices bring the necessity to support massive Machine Type Communications (mMTC) for the Next-Generation networks. One of the enablers for mMTC is the Device-to-Device (D2D) communications. Since it is not possible to reduce the number of devices in massive communications, all the effort for collision and power consumption reduction should be applied to the discovery algorithm of the D2D technologies. The principal D2D technologies are Wi-Fi Direct, Classic Bluetooth, and Bluetooth Low Energy (BLE). However, most of these technologies were not originally designed to support massive communications. The main goal of this work is to assess Wi-Fi Direct, Classic Bluetooth, and BLE performances in terms of number of collisions, energy consumption, and discovery latency, in order to check out the more suitable technology for mMTC scenarios. The results show that Classic Bluetooth is faster than Wi-Fi Direct during the devices' discovery, accelerating network access for the devices in massive communications. Besides, BLE incurs fewer collisions, less energy consumption, and less time for devices' discovery than Classic Bluetooth. Thus, BLE is the more suitable D2D technology—out of the three analyzed in this work—to enable mMTC.

1 INTRODUCTION

IoT is a new technology paradigm capable of offering data analytics and insights, prediction models, and remote monitoring and surveillance. IoT enables countless applications like forecasting upcoming network behaviors through the data retrieved by pools of sensors; establish energy-efficient machine-to-machine communications to achieve low power Wide Area Networks (WAN); enable device-to-device communications to share network resources and locate nearby devices; empower autonomous vehicles communications between cars and with the road infrastructure; monitor equipment health and performance, and protecting physical infrastructure. Therefore, IoT has emerged as the principal enabler for the majority of the large-scale services that will be offered by future networks. All these services require a great number of interconnected devices to collect the big data used for the processing. The higher the number of devices, the higher the network's resources to offer access to every device. However, the current networks by themself have limited resources and they cannot attend the millions of devices. Besides, the IoT devices are resource-constrained especially in terms of energy. Therefore, D2D communications have arisen to efficiently manage the mobile network's resources and overcome link budget problems for ultra-low power devices (Ali et al., 2015).

The D2D communications include short-range wireless technologies like Wi-Fi Direct, Classic Bluetooth, and Bluetooth Low Energy (Ali et al., 2015). In all of them is present a discovery procedure where devices find each other to establish a communication in a specific frequency of the spectrum. During the discovery procedure, every device has two possible roles: inquirer or scanner. An inquiring device periodically sends signals in different frequencies to advertise nearby devices that an inquiring device is looking for some peers to establish communication. A scanning device periodically listens to the signals sent by the device executing the discovery. The scanning device then sends back another signal to let the inquiring device know that the scanning device is available to communicate in the frequency the inquiring device is transmitting the discovery signal. The only way the devices communicate is that the device executing the inquiring task and the device scanning for incom-

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ing discovery signals transmit and receive the discovery signal in the same frequency, respectively. However, the transmission of the discovery signal and the reception of the acknowledge signal are conditioned by other discovery procedures. The more discovery procedures happening simultaneously in the same location, the greater the collision probability and more discovery delay. Therefore, the D2D technology employed in massive communications should address the great number of collisions and high-power consumption experienced by the devices. This paper describes the discovery algorithms of the principal D2D technologies and compares the performances of Wi-Fi Direct, Classic Bluetooth, and BLE, in order to select the more suitable D2D technology to enable massive communications.

The rest of this paper is organized as follows. Section 2 describes the discovery procedures of the principal D2D technologies. In section 3, the Classic Bluetooth and Wi-Fi Direct discovery performances are compared by analyzing the behavior of the two technologies with a developed app. Section 4 describes the details of an additional back-off implemented for Classic Bluetooth to reduce both the number of collisions and the elapsed times during devices' discovery in mMTC scenarios. In section 5, the performances of Classic Bluetooth and BLE are compared by simulating their discovery procedures. Then, section 6 concludes the paper.

2 DISCOVERY PROCEDURES OF THE PRINCIPAL D2D TECHNOLOGIES

Since the discovery procedure of the D2D technologies concerns a lot of signaling, it captures all the attention, especially in massive communications. Therefore, this section describes the algorithms employed by every D2D technology during the discovery procedure.

In the case of Wi-Fi Direct, every device has two states: searching state and listening state. Both states have a random duration of N time units (102.4 ms), where N ∈ {1, 2, 3, ...}. Figure 1 shows the discovery procedure for Wi-Fi Direct. In the searching state, devices broadcast probe requests (discovery requests) in one of the three social channels: 1, 6, 11 in the 2.4 GHz band (Camps-Mur et al., 2013)(Khan et al., 2017). In the same searching interval, the device listens to probe request replies. In the listening state, devices only listen to probe requests in one of the social channels and send back responses in the corresponding cases. The selected channel in the listening state remains constant during the entire discovery process. In this state, devices do not listen to responses of their own past probe transmissions (Sun et al., 2016). In conclusion, a device only discovers a remote device when it receives probe request responses in the searching state.

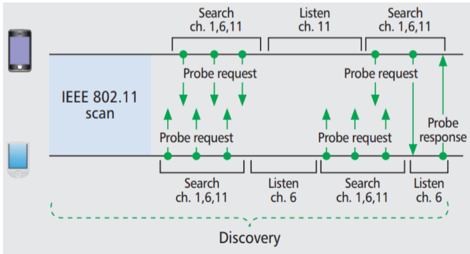

Figure 1: Wi-Fi Direct discovery procedure between two devices (Camps-Mur et al., 2013).

For Bluetooth, the device that starts discovering nearby devices is called an inquiring device. It broadcasts inquiry packets in 32 of 79 possible frequencies. The 32 frequencies are previously agreed upon. The inquiring device keeps sending inquiry packets for two time-slots of 312.5 μs in two different frequencies generated by an internal 28-bit clock, as is shown in Figure 2. The device then listens in the next two subsequent time slots in the same frequencies it sent inquiry packets before. After the listening interval, if the inquiring device does not receive a reply to the inquiry packets, it starts the inquiry packets' broadcast again in two other frequencies. The scanning device uses the 28-bit clock to generate the frequency that the scanning device will use to listen to inquiry packets. The timing used by the scanning device is depicted in Figure 3 (Duflot et al., 2006).

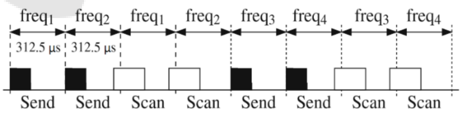

Figure 2: Classic Bluetooth inquiring device's behavior (Duflot et al., 2006).

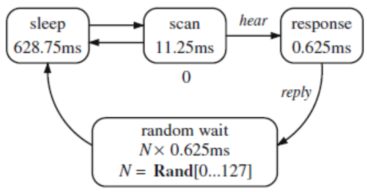

Figure 3: Classic Bluetooth scanning device's behavior (Duflot et al., 2006).

In the case of BLE, there are only three channels used for the discovery procedure. These channels are the 37, 38, and 39. Figure 4 (a, b) summarizes the BLE discovery procedure. On the one hand (Figure 4a), an advertising device sends advertising PDUs over the three channels during an *Advertising Event*. Between two consecutive advertising events, there is a variable *Ta* time, composed by a fixed *advInterval* and a pseudo-random *advDelay*. On the other hand (Figure 4b), a scanning device periodically scans the same three channels to look for advertising signals during a *scanWindow*, which is within a *scanInterval*. In every *scanWindow*, the scanning device scans a different channel from the three channels. The BLE standard states that the *advInterval* should be an integer multiple of 0.625 ms in the range of 20 ms to 10.24 s, the *advDelay* should be within the range of 0 ms to 10 ms, and the *scanInterval* and *scanWindow* shall be less than or equal to 10.24 s (Liu et al., 2012) (Cho et al., 2016).

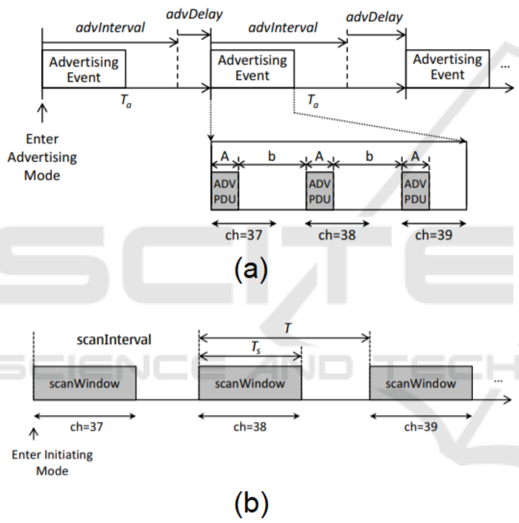

Figure 4: BLE discovery procedure: a) Advertising process and b) Scanning process (Liu et al., 2012).

3 CLASSIC BLUETOOTH AND WI-FI DIRECT DISCOVERY PERFORMANCES COMPARISON

We developed two Android apps to test the Classic Bluetooth and Wi-Fi Direct elapsed times during the devices' discovery and incoming data processing. The apps were tested on the same two devices: Samsung Galaxy S8+ cell phone and a Huawei P9 cell phone. After ten measurements, which is sufficient for the obvious difference in results, the average discovery time for Wi-Fi Direct was 8164 ms. This result is almost five times greater than the Classic Bluetooth discovery time, as shown in Table 1. Therefore, Classic Bluetooth is best suitable to be employed as the D2D technology for enabling mMTC scenarios. However, the Classic Bluetooth discovery procedure can be applied to Wi-Fi to obtain a larger communication range. This means that the Classic Bluetooth discovery algorithm would be used but using the transmission power of Wi-Fi.

The two apps used for Classic Bluetooth and Wi-Fi Direct in this comparison were developed in Qt Creator and Android Studio using the Bluetooth and Wi-Fi Application Programming Interfaces (APIs), respectively. The apps can be found here https://github.com/Abel1027/D2D-Test-Apps.git.

Table 1: Elapsed times in milliseconds for Classic Bluetooth and Wi-Fi Direct to find a remote device in short-range in 10 attempts.

Attempts	Bluetooth (ms)	Wi-Fi Direct (ms)
1	649	8346
2	2659	8630
3	1600	6405
4	898	6335
5	2137	13176
6	4366	7329
7	530	6176
8	3196	9630
9	823	6000
10	373	9613
Mean	**1723.1**	**8164**
Std	**1269.16**	**2130.51**

4 PROPOSED MODIFICATIONS FOR THE CLASSIC BLUETOOTH DISCOVERY PROCEDURE

Since Classic Bluetooth has a shorter elapsed time when discovering nearby devices in comparison to Wi-Fi Direct, Bluetooth is studied for improvement to apply for the discovery procedure in mMTC scenarios. It was simulated an environment where a set of devices (inquiring) tries to find another set of devices on discoverable mode (scanning). In Classic Bluetooth, if more than one device wants to discover other devices and perform the inquiring task and start inquiring with the same sequence of frequencies, their transmissions will collide in every attempt, and they never will find a remote device. Therefore, a back-off is proposed to be added every 11.25 ms (the time needed by a scanning device to listen to incoming discovery messages). The back-off is computed as a random value from [0, 1, ..., 10]×312.5 *mus* where the maximum value is 10×312.5 *mus* = 3.125 ms. The proposed back-off avoids transmissions at the same moment in the same frequency for a discrete simulated environment with a resolution of 31.25 *mus* and a communication latency of 0 ms. In real scenarios, the back-off needs to be calculated depending on the expected latency.

5 PERFORMANCE COMPARISON BETWEEN CLASSIC BLUETOOTH AND BLE DISCOVERY PROCEDURES

We simulated the behavior of the Classic Bluetooth discovery algorithm with the modifications proposed in this work and the BLE discovery procedure. The simulation was deployed by SimPy, a process-based discrete-event simulation Framework used through the Python programming language, using an MSI laptop with a Core i7 processor, a 16 GB RAM, and a 16 GB NVIDIA GeForce RTX 2070 video card. The scripts used for the simulation can be found here: https://github.com/Abel1027/Classic-Bluetooth-vs-BLE.git. The results of the simulation are shown below after computing the average of 10 simulations by variating the random seed in the range 0-9.

Figures 5-8 show the simulation when the number of inquiring devices augments from 10 to 100 in steps of 10 devices, and the number of scanning devices remains the same, in this case, 10 devices. Figures 9-12 show the simulation when the number of inquiring devices remains the same (10 devices), and the number of scanning devices augments from 10 to 100 in steps of 10 devices. The x-axis of the figures shows the number of inquiring/scanning devices. For example, 10/20 means that there are 10 inquiring devices and 20 scanning devices.

Figure 5 shows fewer collisions during the BLE discovery procedure than the Classic Bluetooth discovery procedure. Therefore, the energy consumption and the discovery time are expected to be lower in the case of BLE than in Classic Bluetooth.

The energy consumed by the devices is computed as:

$$E = \frac{P \times m}{R_b} \tag{1}$$

where E is the consumed energy in every transmission given in J, P is the transmission power in mW, m is the number of bits of the transmitted message, and R_b is the bit rate.

The energy consumed by the inquiring devices is calculated from Eq.(1) with P=6.31 mW, m=68 bits, and R_b=1 Mb/s for Classic Bluetooth; and with P=6.31 mW, m=128 bits ⇒ 8 bits (Preamble) + 32 bits (Access Address) + 64 bits (Connectable Undirected Advertising packet) + 24 bits (Cyclic Redundancy Check - CRC), and R_b=1 Mb/s for BLE. The energy consumed by the scanning devices is calculated from Eq.(1) with P=6.31 mW, m=286 bits ⇒ 72 bits (Access Code) + 54 bits (Header) + 144 bits (Payload) + 16 bits (CRC), and R_b=1 Mb/s for Classic Bluetooth; and with P=6.31 mW, m=176 bits ⇒ 8 bits (Preamble) + 32 bits (Access Address) + 112 bits (Connectable Directed Advertising packet) + 24 bits (CRC), and R_b=1 Mb/s for BLE.

From Figure 6, the energy consumed by the inquiring devices is less for the BLE case than for the Classic Bluetooth case. The same occurs for the energy consumption of the scanning devices (see Figure 7).

Figure 8 shows that the total time elapsed during the discovery procedure is less for the BLE case than for the Classic Bluetooth case. In the BLE case, the discovery time is below 10 seconds while the discovery time for the Classic Bluetooth case is above 10 seconds.

From Figure 9, there are fewer collisions during the BLE discovery procedure than the Classic Bluetooth discovery procedure. Therefore, the energy consumption and the discovery time are expected to be lower in the case of BLE than in Classic Bluetooth.

The energy consumed by the inquiring devices is less for the BLE case than for the Classic Bluetooth case, as it is depicted in Figure 10. The same occurs for the energy consumption of the scanning devices (see Figure 11).

Figure 12 shows that the total time elapsed during the discovery procedure is less for the BLE case than for the Classic Bluetooth case. In the BLE case, the discovery time is below 1 second when the number of scanning devices is greater than 20 while the discovery time for the Classic Bluetooth case is always above 10 seconds.

6 CONCLUSIONS

The D2D communication technologies have arisen as the enablers of the massive communications for the Next-Generation networks. Most of the available

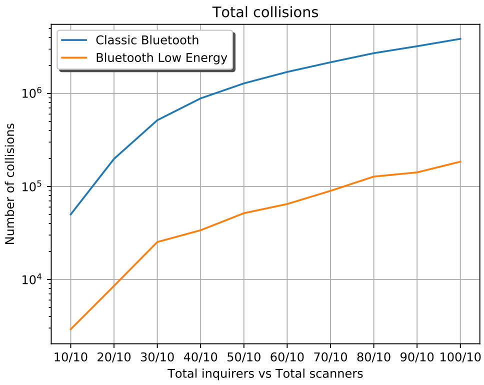

Figure 5: Total number of collisions during the discovery procedure when the number of inquiring devices increases and the number of scanning devices remains the same.

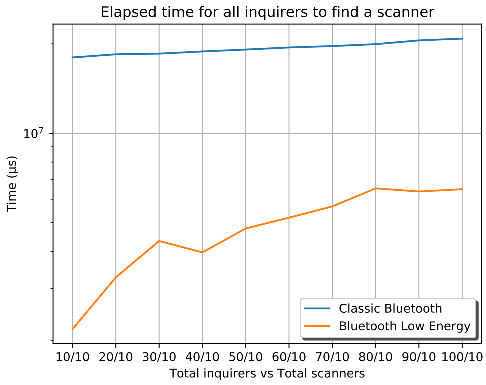

Figure 8: Total elapsed time for all inquiring devices to find a scanning device during the discovery procedure when the number of inquiring devices increases and the number of scanning devices remains the same.

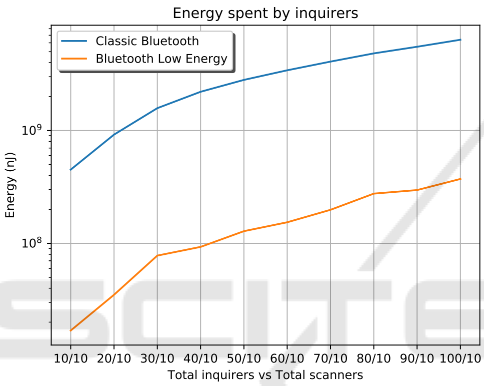

Figure 6: Total energy spent by the inquiring devices during the discovery procedure when the number of inquiring devices increases and the number of scanning devices remains the same.

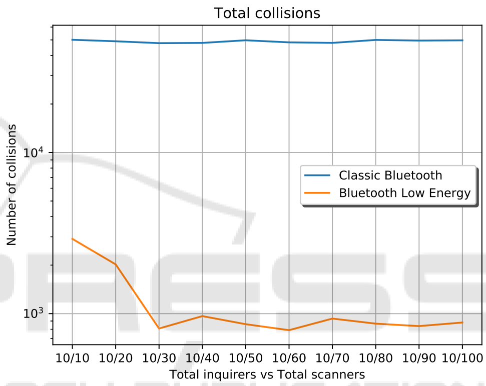

Figure 9: Total number of collisions during the discovery procedure when the number of inquiring devices remains the same and the number of scanning devices increases.

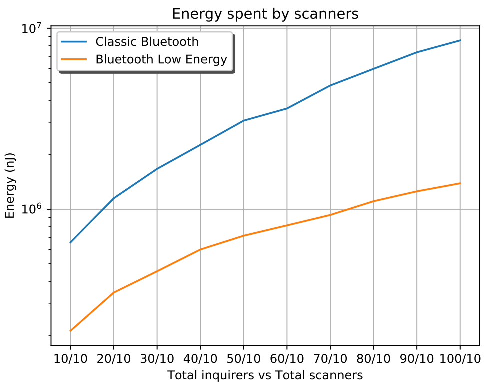

Figure 7: Total energy spent by the scanning devices during the discovery procedure when the number of inquiring devices increases and the number of scanning devices remains the same.

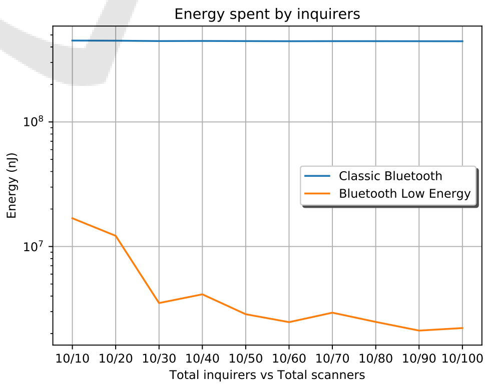

Figure 10: Total energy spent by the inquiring devices during the discovery procedure when the number of inquiring devices remains the same and the number of scanning devices increases.

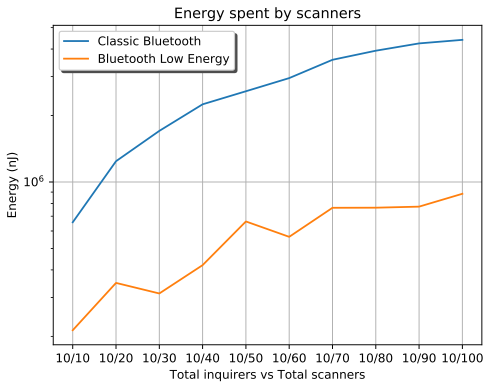

Figure 11: Total energy spent by the scanning devices during the discovery procedure when the number of inquiring devices remains the same and the number of scanning devices increases.

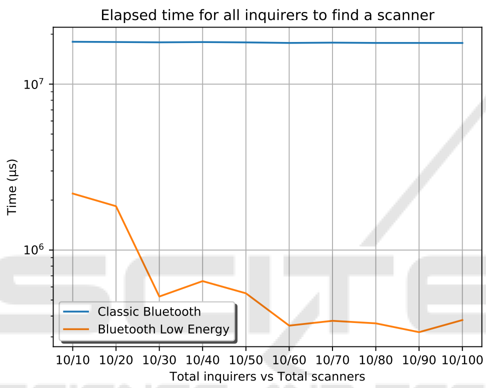

Figure 12: Total elapsed time for all inquiring devices to find a scanning device during the discovery procedure when the number of inquiring devices remains the same and the number of scanning devices increases.

D2D technologies were not originally conceived to support such a massiveness of devices trying to connect with each other. Other D2D technologies were born to handle mMTC scenarios, but they are not standardized yet. Therefore, it is useful to analyze, test, and assess the available D2D technologies to check out the technology with the best performance during the discovery procedure, which is the process with more signaling.

In this work we compared the discovery procedures' performances of Wi-Fi Direct and Classic Bluetooth. Then, we compared Classic Bluetooth with BLE. The results show that Classic Bluetooth was 5 times faster than Wi-Fi Direct during the devices' discovery. However, Classic Bluetooth is slower than BLE. BLE also experiences fewer collisions and consumes less energy than Classic Bluetooth during the devices' discovery. BLE allows that around 100 inquiring devices find at least 1 scanning device out of 10 scanning devices in less than 10 seconds. BLE also allows that around 10 inquiring devices discover at least 1 scanning device out of 100 scanning devices in less than 1 second, in contrast with the 10 seconds the Classic Bluetooth takes to do the same task. Therefore, BLE is faster and consumes less energy than Bluetooth, and Wi-Fi by transitivity. For these reasons, BLE is one of the most promising D2D communication technologies—out of the three analyzed in this work—for enabling mMTC in the Next-Generation networks. However, BLE is a very short-range D2D technology, and it has some security vulnerabilities during the pairing procedure which can be overcome by other D2D technologies like LTE-Direct.

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