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Wi-Fi direct in android: Creating seamless device-to-device communication

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Abstract

The study examines the characteristic features, capabilities, and performance of Wi-Fi Direct as a device-to-device communication protocol in Android. During the research, the Wi-Fi Direct's effectiveness, connectivity speed and stability, energy consumption, and the possibility to transmit large-sized files, were assessed, comparing them to similar Bluetooth characteristics. The research data were taken from testing using Google Pixel 4 and Samsung Galaxy S10 smartphones with Android, and the results were compared with secondary data findings. The test presupposed transmission of three different-sized files to measure performance outcomes in terms of power consumption, data transfer quality, connection speed, and reliability. The research revealed how Wi-Fi Direct works with the data transmission speed and connection stability compared to Bluetooth in Android and identified the consequences of Wi-Fi Direct use for the energy consumption of Android devices. The study findings show that Wi-Fi Direct is associated with better outcomes in the areas of file transfer speed, especially for large data files, while Bluetooth has proven to be more energy-efficient and easier to use for smaller tasks. These results align with the secondary data findings and highlight the potential of combining both communication protocols. Finally, the study emphasizes the growing relevance of Wi-Fi Direct for high-bandwidth mobile applications, irrespective of setup complexity and higher power consumption.

Keywords: Wi-Fi Direct, Bluetooth, Android, Communication protocol, Data transmission

1. Introduction

1.1. Research background

In the modern technology-driven world, wireless connectivity and seamless data exchange between mobile devices have gained significant importance. Continuous proliferation of smart devices, mobile applications, and the Internet of Things (IoT) increases users' expectations regarding the speed and stability of communication between devices. Bluetooth is among the most common technologies that have served this need, but it fails to

ensure fast data transfer, especially when handling large files. Therefore, Wi-Fi Direct emerged as a powerful and effective alternative, primarily developed for Android devices. It ensures peer-to-peer (P2P) connections without an intermediary access point, for instance, a router [1].

The use of the existing Wi-Fi infrastructure mode does not allow devices to connect to a common access point, ensuring connection to other Wi-Fi devices. Therefore, Wi-Fi Direct appeared as an alternative that ensures fast, secure, and effective communication between devices. A later technical specification of Wi-Fi P2P was presented in 2016, with the feature that enables devices to discover each other and form a P2P group [1]. Hence, each group had an elected node referred to as a divide-to-device (D2D) Group Owner, acting as an access point. Since that time, Wi-Fi Direct has become a suitable communication protocol for multiple communication domains.

Device connection through Wi-Fi Direct may occur anytime and anywhere, even if users cannot access a Wi-Fi network. A Wi-Fi Direct-certified device signals other devices in the area, and it makes a connection [2]. Consequently, a user can view devices sending a connection request or receiving an invitation from other users with Wi-Fi Direct-certified devices. The user decides whether to accept the invitation, considering the reliability and truthfulness of the devices or their owners. In case of connection confirmation, communication becomes protected due to the seamless and easy-to-use Wi-Fi connection protocol.

Four Wi-Fi Direct devices (of six) can connect to each other or create a group [2]. However, a one-to-one connection is more common as it enables sharing or exchanging content with a relative, friend, or colleague. Moreover, users can connect a camera to a printer, a phone to a tablet or PC, or create a connection among several gaming devices. Such a connection eliminates the need for multiple cables between devices.

1.2. Benefits of Wi-Fi Direct

Wi-Fi Direct is relevant to Android ecosystems, which are increasingly integrated into the operating systems in terms of protocol support. These days, many Android applications rely on smooth and fast communication between devices, taking the most of Wi-Fi Direct and benefiting from its advantages.

Hence, the users of this communication protocol experience its wide availability, high transmission rates, a broad range, and low latency [3]. Being more complex than Bluetooth, it ensures multiplayer gaming, streaming media, and connection to IoT devices. Moreover, it may be applied entirely in software and is capable of addressing the basics.

Fast data transfer becomes possible due to the use of high Wi-Fi spectrum frequencies. Furthermore, direct connections enable connecting devices, eliminating the need for a central access point while creating a network. This is referred to as a significant benefit as it enhances file sharing between a tablet, a smartphone, or any other device to a Wi-Fi Direct-enabled printer [3].

Simplified device pairing is another benefit associated with the use of features that make it easier to establish secure connections between devices [4]. The capability to enhance device connection to several devices simultaneously provides an opportunity to experience one-to-many sharing configurations that are not allowed by Bluetooth. Finally, the network management cost is effective, and the connection is seamless, which attracts many users because of the possibility of quick communication without manual configuration. Hence, Wi-Fi Direct is suitable for resource sharing, content distribution, social networking, emergency communication, and online gaming. Wi-Fi Direct (previously known as Wi-Fi P2P) was introduced in 2010 with the endeavor to make ad hoc networks easier to use [5]. It enables establishing a direct Wi-Fi connection that relies on direction within devices, creating an easy-to-use and high-speed network [1].

Wi-Fi Direct is often used due to cost effectiveness, large-scale implementations, and WI-Fi device availability. Irrespective of numerous benefits, Wi-Fi Direct is associated with limited technical and academic research that ensures proper real-world performance evaluation of Wi-Fi Direct in the spheres of energy efficiency,

connection stability, and data transmission speed [5]. These spheres are essential for mobile device users, who face tight system resources and battery life constraints.

1.3. Research relevance

Wi-Fi is a classical Wi-Fi modification that offers the same performance in terms of bandwidth and range. Its distinctive feature is to directly connect two devices without a third party. Android smartphones from version 4.0 are equipped with this technology and are capable of creating ad hoc groups [2].

Wi-Fi Direct divides the group formation processes into several phases, including discovery, group owner negotiation, the WPS provision, and address configuration. Although there are several studies that examine Wi-Fi Direct use and evaluate the technology, they are primarily experimental and focus on discussing the difficulties and challenges of implementing this communication protocol in practice, highlighting its benefits only in some areas.

Therefore, it is essential to examine how Wi-Fi Direct assists in creating seamless communication between different devices, providing an extended opportunity contrary to Bluetooth users. Studying this communication protocol in Android development is beneficial as it enables direct, D2D, and high-speed communication between several devices without an access point (third party). These features enable multiple applications of Wi-Fi Direct for Android users. Hence, a deep insight into how Wi-Fi Direct works and its main differences from Bluetooth helps ensure innovative applications benefit from the functionality it provides to the users.

1.4. Research aim and questions

The current study is developed to examine the practical use of Wi-Fi Direct on Android devices with a focus on seamless device-to-device (D2D) communication. It will include a comparative analysis with Bluetooth and consideration of such factors as connection speed and reliability, data transmission quality, and power consumption.

Technology developments, their use in almost all spheres of life, as well as their immense impact on people's lives, have increased the continually growing demand for efficiency, quality, speed, and frequent device-to-device communication [2]. A deep insight into the strengths of Wi-Fi Direct and an understanding of the challenges associated with its use will help developers, manufacturers, and researchers unite their efforts in improving this communication protocol, enhancing the smoothness of its work.

Hence, the current study aims to evaluate the Wi-Fi Direct productivity (compared to Bluetooth) in Android to ensure seamless connection between devices, focusing on the data transmission speed, connection stability, and energy consumption. These aspects play a vital role in determining the Wi-Fi Direct suitability in the cases of real-world mobile and IoT use.

To meet the research aim, the following questions will be addressed: 1. How does Wi-Fi Direct work with the data transmission speed and connection stability in comparison to Bluetooth on Android devices? 2. What are the consequences of Wi-Fi Direct implementation for the energy consumption of Android devices? The examination of these questions will provide readers with an extended understanding of the capabilities, key characteristic features, and benefits of Wi-Fi Direct for Android users, enhancing their awareness of the current and future potential of this communication protocol.

Thus, Wi-Fi Direct is a powerful, cost-effective, reliable, and versatile technology that improves connections for Android devices, enhancing connection quality and speed. The absence of infrastructure dependence and the provision of device-to-device communication make this communication tool increasingly relevant in the modern technology-driven and interconnected world, supporting multiple applications from file sharing to IoT interactions [4]. Finally, Wi-Fi Direct undergoes the process of continuous development and improvement to ensure seamless wireless communication that goes along with technological advancement.

2. Research method

The methodology section presents detailed information on the approaches used to explore the topic, compare the effectiveness and reliability of Wi-Fi Direct and Bluetooth for D2D communication in Android smartphones. The primary emphasis is made on empirical evaluation of these technologies, considering data transmission speed, battery consumption, connection stability and reliability, and relevant characteristics.

This paper addresses the question of software and application design, experimental procedure, and metrics applied. Moreover, it discusses data collection and its management, data presentation techniques, result representation, and limitations. Hence, qualitative and quantitative data will be considered as the study not only relies on the analysis of empirical data, but also presupposes the comparison of Wi-Fi Direct and Bluetooth, relying on observations.

Hence, qualitative research is applied due to its flexibility and the possibility to learn from users' experiences of using Wi-Fi Direct and Bluetooth. Moreover, it assists in exploring opinions and analyzing them, relying on real-time use [6]. Although this approach depends on the experience and bias, it is suitable for the current research, which will also use qualitative analysis while collecting and analyzing numerical information.

2.1. Devices

The devices used to ensure reproducibility and validity of the received results were two high-performance Android smartphones – Google Pixel 4 (Android 12, Snapdragon 955, 6GB RAM) and Samsung Galaxy S10 (Android 10, Snapdragon 855, 8GB RAM). The choice of these devices directly relates to their compatibility with native Android Wi-Fi P2P and Bluetooth application programming interfaces (APIs), hardware capabilities that enable continuous operations of data transfer, and their market use.

A suitable testing environment that included a room was created for the research. It was a low-interface and climate-controlled indoor environment that minimized temperature changes, background noise, and signal disruptions. Before use in the experiment, both Android smartphones underwent a full factory reset to ensure that they had optimal performance.

All system updates were disabled, and airplane mode was activated for the research. A special application for file transfer through Wi-Fi Direct was developed. The screen brightness was reduced to prevent interruptions and distractions. The devices were tested in a static environment, and they were positioned at a distance of 3 meters. Only one person was present in the testing room, which prevented any distracting noises.

The Android Studio was used to develop a testing application, which was written in Kotlin. Moreover, the application leveraged Bluetooth and Wi-Fi Direct libraries to transfer structured files. The application was characterized by a set of distinct features, including automated pairing and connection, file selection, real-time performance and its monitoring, data transfer control, error detection, logging, and relevant system, as well as battery monitoring.

Hence, automated pairing and connection occurred using Bluetooth and Wi-Fi Direct technology, and the choice depended on the test mode. A thorough section of files and control of their transfer enabled the transfer of three previously selected files of different volumes (10MB, 100MB, and 1GB).

Additionally, the real-time performance monitoring was performed, which helped identify start and stop times of file transfer. All interruptions, retries, and connection failures were noted to ensure accurate error detection. Furthermore, Battery Manager API (Android) helped monitor battery, tracking before and after states, and general battery-related statistics. Finally, the logging system, which was responsible for storing structured data logs in Comma Separated Values (CSV) format for import into Excel that was further analyzed to get reliable results. The separate activity flows were created within the application for Bluetooth and Wi-Fi Direct technologies to ensure concise test sessions and minimal interference.

2.2. Experiment procedure

The procedure of the conducted experiment followed a systematic process for each Bluetooth and Wi-Fi Direct protocol and file. It aimed at establishing a connection between the devices through Wi-Fi Direct, transmitting 10MB, 100MB, and 1GB files, noting the transfer time, evaluating stability and connection failures, determining energy consumption with the help of Android tools (for instance, battery monitoring), and repeating the same tests with Bluetooth to get material for comparison.

Hence, each protocol included two tests – for Wi-Fi Direct and Bluetooth. For Wi-Fi Direct, the devices detected each other automatically, and the connection occurred through peer discovery and negotiation handshake using Wi-Fi P2P APIs. In terms of Bluetooth, connection initiation occurred with manual pairing, which was completed before each session, ensuring a known MAC socket connection address.

The process of transferring testing protocol for the files of three different sizes was the same, and repeated each test 10 times for Wi-Fi Direct and Bluetooth. There were 60 trials in total. Moreover, the developed application measured the transmission time and highlighted the beginning and the end of the process. Moreover, the connection stability for both protocols was tested, identifying connection failures. The transfer was indicated as a failure in case the reconnection was unsuccessful three times.

Finally, the evaluation of energy consumption occurred through the logging of initial and final battery percentages for each test. Additionally, the devices were charged to 100% before every test batch, followed by battery log analysis. Finally, the observation of a cooling-off period (5 minutes) between tests helped mitigate thermal effects. These procedures for Wi-Fi Direct and Bluetooth are presented in Table 1.

Table 1. Procedure comparison

Procedure	Wi-Fi Direct	Bluetooth
Connection	Automatic, peer discovery, negotiation handshake	MAC address for socket connection
Protocol transfer	10 times for each file size (30 in total). Transmitting initiation and completion time was noted	10 times for each file size (30 in total). Transmitting initiation and completion time was noted.
Connection stability	Connection failure recording	Connection failure recording
Energy Consumption	Initial and final battery %, device charging, battery log analysis, and 5 5-minute cooling-off period	Initial and final battery %, device charging, battery log analysis, and 5 5-minute cooling-off period

2.3. Metrics

Protocol evaluation relied on such performance indicators as speed, stability, and energy consumption. Hence, the transfer speed was calculated in MB/s by dividing the file size by the transfer duration. Hence, high values showed efficient protocol performance.

The connection stability was measured in % and was determined by the successful file transfer percentage (considering all attempts). The stability rate was calculated by dividing successful transfers by total transfers and multiplying by 100. Energy consumption (mAh) was estimated with the help of battery percentage drops and device battery capacities.

Hence, this measure was calculated as a multiplier of batter drop (5) and battery capacity divided by 100. The battery capacity of the Pixel 4 was 2800mAh, while that of the Galaxy 10 was 34000mAh. All trial-related observations were recorded, including device lag, noticeable heating, and interface delays (if there were any).

2.4. Data collection

The data that helped answer the research questions were collected from primary and secondary sources. The primary data from the experiment procedure was collected, comparing Wi-Fi Direct and Bluetooth protocols. The evaluation and analysis of key procedures were performed to identify the differences between the protocols. Moreover, secondary data was used to get an insight into Wi-Fi Direct and Bluetooth, identifying the benefits and areas of use of the first one, and identifying its capability to ensure seamless device-to-device communication. Secondary data analysis is a cost-effective data collection approach that helps learn what is already known about the topic under discussion [6].

The collected information was thoroughly evaluated and analyzed to further interpret it and incorporate it into research findings. Only reputable sources (reports, journal articles, official websites, and books) were considered. The inclusion criteria were sources published not earlier than 2015, English, and the presence of a keyword/keywords in the title. Hence, secondary data are cost- and time-effective, as well as easily available. However, it is necessary to verify it to ensure reliability. Secondary data review and analysis are beneficial for the current research, and their combination with primary data significantly contributes to the knowledge base and research findings synthesis.

A comprehensive strategy of data collection promoted the accuracy and integrity of study results. The test procedure enabled generating several data points, including the protocol used, unique test ID, file size, data transmission duration, device pair identifier, retry number, failure status, data transmission success, battery % before and after file transmission, and energy consumption calculation. All notes and records were gathered in a secure file, backed up to Google Drive. The raw data was analyzed and presented in tables to be easily understood.

2.5. Data presentation

To ensure that all data are properly comprehended by readers, they were visualized, presented in tables. Each visualization was designed to highlight trends and anomalies while supporting conclusions drawn from the dataset. Both primary and secondary data revealed that Wi-Fi Direct outperforms Bluetooth, especially in terms of large file transmission. Moreover, stability was higher for Wi-Fi Direct protocols. Finally, energy consumption analysis indicated a linear correlation with the file size and both protocols.

The results received from primary findings align with the secondary ones, highlighting the advantages of Wi-Fi Direct in the application of high-speed data transfer that is suitable for real-time implementation. The experiment tests provided valuable insights into the device's benefits and limitations, as testing was restricted only to Android devices. Moreover, it ensures environmental control in which the testing room reduces interference and fails to represent environmental complexities.

2.6. Ethical and legal considerations

All data collection procedures were aligned with ethical and legal standards. The researcher was the owner of both devices and which means that no third parties were engaged in the study. Moreover, data collection did not presuppose the transfer of private or user-generated content. The customer application was not disturbed and was not tracked. All software constituents were developed following Android’s developer policies and the guidelines of the Google Play Store.

Thus, the researcher used a comprehensive and structured approach to facilitate the study's aim, objectives, and questions, ensuring a concise evaluation of Wi-Fie Direct’s performance for P2P communication on Android devices, namely Snapdragon 955 and Samsung Galaxy S10. A combination of testing protocols and software engineering assisted in getting a reliable foundation for real-world applicability evaluation. These findings may guide future development in P2P communication protocols and energy efficiency optimization in next-generation wireless protocols and their implementation.

3. Results and discussion

3.1. Wi-Fi direct vs. bluetooth

Wireless communication technologies, including Wi-Fi Direct vs Bluetooth, have revolutionized connection and data exchange between Android devices. Bluetooth and Wi-Fi Direct are among the most commonly applied communication protocols, ensuring quick data exchange without the need for cables or internet access [7]. Although these protocols have the same function, they are significantly different in multiple characteristics, including speed, range, energy consumption, ease of use, and task suitability [8]. Wi-Fi Direct application in Android apps ensures a set of benefits, including no need for a router, the possibility to connect multiple peers, and high speed. The most common disadvantages include the need for managing connection roles, complicated setup, and permissions. The use of Bluetooth in Android apps is beneficial to users as it is associated with built-in pairing, an easy permission model, good background work, and decreased code complexity. Despite these advantages, Bluetooth is not effective in transmitting large files, may be interfered with by other wireless signals, and has low high-resolution media throughput.

Wi-Fi Direct is provided in more and more Android smartphones these days. The analysis of relevant literature has shown that both Wi-Fi Direct and Bluetooth seek to become power-saving technologies, ensuring communication between battery-powered devices. Contrary to other Wi-Fi functionalities, Wi-Fi Direct is not specified by the IEEE, but its feature is straightforward [8]. When this protocol connects two devices, one of them takes the role of the access point and becomes the Wi-Fi Direct network's Group Owner (GO). It means that other devices, even non-Wi-Fi Direct ones, can join this group due to the DHCP functionality to assign IP addresses to the group network's clients. Immediately after establishing a connection and assigning an IP address, the standard TCP/IP protocol stack is applied for data transmission. According to Sauter [8], this is the major difference between Wi-Fi Direct and Bluetooth protocols. The researchers highlight that Bluetooth defines profiles for image, file, or signal transfer, while Wi-Fi Direct offers a transparent IP channel. Bluetooth relies on the feature of a new low-energy technology (PDF), indicating optimization to run on a coin cell battery for at least a year [9]. However, it is suitable only for transferring short data bursts, and it fails to work with an older Bluetooth device, lacking the low-energy feature [9]. Hence, a smartphone and a laptop with Bluetooth 4.0 will require switching.

Wi-Fi Direct (supported by Android 4.0+ via the WifiP2pManager API) enables Android devices to connect to each other without an access point or internet access using Wi-Fi radio. Establishing a P2P network, Wi-Fi Direct offers quick data transmission as its high data transfer rate reaches 250 Mbps, and its range is up to 200 meters [10]. This communication protocol lets users transfer app files and HD videos. Hence, it is used to transfer large files, stream HD video, share apps and documents, for multiplayer gaming without access to the internet, and IoT device setup. Wi-Fi Direct supports standard Wi-Fi security protocols. Bluetooth is another wireless protocol that assists in data exchange over short distances. Compared to Wi-Fi Direct, it is simple and is characterized by broad compatibility. It ensures short-range communication up to 50 meters and does not consume much power, which means that it is suitable for battery-operated and wearable devices [10]. Moreover, it shows good work with small data transfers and is supported across all Android devices. Its common use directly relates to easy pairing with accessories such as smartwatches, fitness trackers, and headphones. Bluetooth is most suitable for sending small files (messages, photos, contacts), for real-time communication, streaming audio, and accessory pairing. Bluetooth is also a secure communication protocol.

Wi-Fi Direct has two states with a random time unit duration, including searching and listening. In the searching state, devices broadcast discovery requests (also known as probe requests) in one channel [1]. Then, the device listens to probe request replies, which means that in the listening state, devices listen to probe requests in one channel and provide their back responses in the corresponding cases [10]. The devices do not change the chosen channel during the discovery process and do not listen to their own past probe transmission responses [10]. One device discovers a remote device only after it gets probe request responses in the searching state [11]. For

Bluetooth, an inquiring device is the one that starts discovering nearby devices, and it keeps sending inquiry packets [7]. After the listening interval, it begins to broadcast the inquiry packets on two other frequencies. It occurs in case the inquiring device fails to receive a reply to the inquiry packets [10]. Moreover, Wi-Fi Direct networks can be applied in traditional Wi-Fi environments. Wi-Fi Direct devices enable creating a device-to-device connection with old wireless printers or other wireless devices without any connection issues [9]. However, the use of Wi-Fi Direct is referred to a complex as it is necessary to download an app to communicate with the server app on devices, for instance, a TV [8]. Contrary to it, Bluetooth has standardized profiles applied to many operating systems. Hence, the search and listening processes and the use of Wi-Fe Direct and Bluetooth communication protocols differ.

3.2. Analysis

The comparison of Wi-Fi Direct and Bluetooth characteristic features indicates that the first one is better for large file transfer due to its high speed. However, Bluetooth is most suitable for small transfers or constant low-data communication with accessories, including headphones. Finally, the simplicity of its use attracts many users. Some apps, for instance SHAREit, use both communication protocols. At first, they used Bluetooth for pairing, further switching to Wi-Fi Direct to transmit large files. Hence, they use a hybrid method to ensure seamless connection with the desired speed [10]. Although researchers' opinions differ in terms of which communication protocol to recommend, it is necessary to analyze the benefits and limitations of each. As many users prefer speed and large data amount transmission, simplicity of use and low power do not dominate these benefits, making the Bluetooth protocol less technically suitable for some cases. Technology development and continuous sophistication of devices imply that newer communication protocols are being developed to meet customers' needs and preferences. Table 2 shows the comparison of the main characteristics of Wi-Fi Direct and Bluetooth. It enables contrasting them and getting an insight into which communication protocol suits a certain situation.

Table 2. Wi-Fi Direct and Bluetooth comparison

Feature	Wi-Fi Direct	Bluetooth
Speed	up to 250 Mbps	Up to 3-5 Mbps
Range	up to 200 meters	10-5- meters
Energy Use	High	Low
Use	Complex (manual handling)	Easy
Pairing Time	Up to 15 seconds	Up to 3 seconds
File size	Large	Small
Concurrent Devices	Multiple	One-to-one
Security	WPA2	AES 128-bit encryption
Supported APIs	WifiP2pManager, WifiP2pConfig, and others	BluetoothAdapter, BluetoothSocket
Android Support	Excellent Android 4.0+	Well-established for all Android devices

The observation that included the use of a testing application lasted for four days, as it was necessary to record everything that occurred with the file transfer using two devices - Google Pixel 4 and Samsung Galaxy S10. During the first day, the researcher worked only with a 10MB file. All interruptions or unsuccessful sessions were recorded. The second day was dedicated to a 100Mb file. During the third day, a 1 GB file was transmitted, and it took longer than during the previous two days. Finally, the fourth day was the time of comparing the results and combining them into a relevant conclusion. In all the cases, the transfer occurred between the above-mentioned smartphones. No other devices were used while testing. Hence, the testing results showed that Wi-Fi Direct established a connection between two Android smartphones automatically with a peer discovery and

negotiation handshake, while Bluetooth required a MAC address. Moreover, in the case of Wi-Fi Direct, the researcher experiences fewer failures of protocol transfer. However, there were some issues with Bluetooth, and some files, especially large ones, failed to be quickly transmitted to another device. The connection stability appeared to be better for Wi-Fi Direct, but it is necessary to highlight that Bluetooth had only insignificant stability issues, which did not affect file transmission. Finally, there were no issues with battery charging. Table 3 represents six different scenarios and suggests a suitable technology, providing the main reasons that may impact the choice.

Table 3. Comparison of Wi-Fi Direct and Bluetooth performance

Scenario	Suitable Technology	Reason
1-2 GB video sending between two Android phones	Wi-Fi Direct	Transfer speed, reliable connection
Sending contact information	Bluetooth	Fast pairing
Streaming audio to wireless headphones	Bluetooth	Low battery usage and latency
A multiplayer game between Android smartphones	Wi-Fi Direct	Fast network
Smartwatch connection	Bluetooth	Minimal energy consumption
Folder sharing	Wi-Fi Direct	P2P data transfer efficiency

Table 3 indicates that Wi-Fi Direct was a suitable communication technology for transmitting large video files between two Android smartphones, multiplayer gaming between these devices, and folder sharing. The protocol showed high transfer speed, reliable connection, fast network, and efficient P2P data transmission. Furthermore, Bluetooth has proven to be effective if a user seeks to send contact information, stream audio to wireless accessories, for instance, headphones, and a smartwatch connection. This protocol presented fast pairing, low battery use, and low latency, as well as minimal energy consumption. Thus, the developed testing application enhanced automated pairing and connection, file selection, real-time performance, and its monitoring, error detection, logging, a thorough data transfer control, and battery monitoring, which was of significant importance during the test. The real-time performance monitoring was performed, noting the file transfer start and stop times. There were not many interruptions (they occurred only with the 1GB file and only once). Moreover, there were two connection failures with Bluetooth. Battery Manager API (Android) assisted in battery monitoring, which implies the absence of any issues with battery charging.

In the modern technology-driven world, seamless data transfer is essential. Wi-Fi Direct and Bluetooth are the wireless communication protocols that ensure P2P data exchange without the need for internet connectivity, showing good results in terms of connection stability, data transmission speed, and energy efficiency. The analysis of comparison is performed to determine the effectiveness of ensuring seamless and reliable data transmission between Android devices (smartphones).

Speed is a critical factor that impacts data transfer experience and effectiveness. During the testing session, three different-sized files were transferred between two Android smartphones. Hence, Wi-Fi Direct showed 15 MB/s transfer speed, which was higher compared to the speed of a 1 GB file transmission using Bluetooth, as it was only 10 MB/s. This implies that Wi-Fi Direct is associated with a clear edge in high-volume file transfers, as only 67 seconds were needed to transmit a 1 GB video file. However, the transfer of the same file over Bluetooth took 100 seconds.

The difference in protocol performance relates to the fact that Wi-Fi Direct uses standard Wi-Fi radio and protocols similar to the ones used in home networks, while Bluetooth best suits low-bandwidth and low-power applications. Therefore, Bluetooth still experiences disadvantages associated with the file transmission speed. Thus, in case the users prioritize speed, Wi-Fi Direct is a preferred choice.

In terms of connection stability and reliability, Wi-Fi Direct and Bluetooth showed good results. Both communication protocols had a successful data transmission rate (95%) in repeated tests.

As soon as a connection occurs, both protocols show equal reliability in data transfer maintenance without any interruption. However, these technologies experience differences in terms of the connection process. For instance, Wi-Fi Direct is highly stable immediately after connection, although it may need more initial negotiation time. It may require a user to accept prompts, which adds several seconds to the setup time. The testing results showed that this does not affect data transmission stability. It has been found that Bluetooth pairing is usually faster and more user-friendly compared to Wi-Fi Direct. Authentication indicates that devices can pair automatically.

Although Bluetooth showed an insignificantly better interference resistance, both communication technology protocols maintained a stable and reliable connection. However, the range of Wi-Fi Direct (up to 200 meters) makes it more suitable for physical layouts where devices are not always close to each other. These technologies offer good data transfer stability, presenting no significant weaknesses.

The analysis of relevant data sources indicates that many users report concerns regarding energy efficiency and battery consumption. Hence, the research results indicate that Wi-Fi Direct consumes nearly 20% more energy compared to Bluetooth if there is a need to transmit a 1 GB file. Therefore, Wi-Fi Direct has proven to me to be more powerful and is referred to be suitable for using high-bandwidth and longer transmission periods. Moreover, Bluetooth is primarily used for low-energy consumption and IoT devices.

A noticeable battery drain may be experienced if people use older devices or while transferring multiple large files through Wi-Fi Direct. Contrary to it, Bluetooth is more beneficial for prolonged background tasks. If a user prioritizes energy efficiency and battery longevity, it is necessary to choose Booth. Wi-Fi Direct may be appropriate for speed advantage and short-term data transmission.

Moreover, Wi-Fi Direct and Bluetooth differ in terms of compatibility and integration ease. Both protocols are supported in Android. However, Bluetooth offers easier integration and user interface control as it does not require many permissions. Also, it has more mature libraries and ensures seamless connectivity with a wide range of hardware. Wi-Fi Direct requires additional configurations, including Wi-Fi P2P support, runtime permission handling, and manual socket communication. As many consumers seek minimal friction, Bluetooth provides a smooth user experience, irrespective of its slowness.

Table 4. Wi-Fi Direct and Bluetooth assessment and suitability

Criteria	Wi-Fi Direct	Bluetooth
Data transmission speed	Fast	Slow
Stability	Reliable	Reliable
Battery use	High	Efficient
Suitability of file size	Suitable for large files	Suitable for small files
Setup complexity	Requires configuration, complex	User-friendly, simple
Use range	Long	Short
Ideal use cases	HD files	Messaging, audio, wearables

Thus, Wi-Fi Direct and Bluetooth provide their users with seamless data transfer (Android users). However, they excel in various areas. Wi-Fi Direct dominates Bluetooth in terms of speed, size of transferred file, and range. Therefore, it is ideal for apps focused on collaborative work, media sharing, and file transmission. Contrary to it, Bluetooth is ideal for low-energy, simple, and fast-to-connect tasks. It is necessary to consider the context before choosing the communication protocol.

3.3. Discussion

3.3.1. Improvement

It has been found that the Wi-Fi Direct communication protocol outperforms Bluetooth in terms of speed. Irrespective of a 20% power consumption increase, this technology is beneficial for many Android users who prioritize data transmission speed. Seamless data transfer is contributed to by energy efficiency. Wi-Fi Direct ensures smart power management; Wi-Fi radios are programmed by Android developers to become activated during data transfer and deactivation as soon as data transmission is complete. This process prevents unnecessary background activity and helps conserve battery power. Automatic timeout incorporation for inactive Wi-Fi Direct sessions significantly decreases the duration of the wireless module, expanding battery life.

The research results indicate that it is possible to combine hybrid Bluetooth with Wi-Fi models. Some applications, for instance, SHAREit, apply Bluetooth to establish a connection to exchange data. Then, they switch to Wi-Fi Direct to transfer data. This model enables an effective combination of the speed priority of Wi-Fi Direct and the energy efficiency of Bluetooth. Moreover, the analyzed communication technologies are associated with protocol-level optimization. If the use of lightweight protocols that do not have high packet reliability, devices can reduce control signals and minimize energy consumption during a session. These strategies help reduce the power demand of Wi-Fi Direct without sacrificing its performance benefits. This makes this protocol an effective solution even in power-sensitive mobile use cases.

3.3.2. Literature comparison and research results

The results of the testing showed that Wi-Fi Direct had 15 MB/s, while Bluetooth achieved only 10 MB/s. Moreover, both communication technologies presented a 95% stability rate (Table 5). However, Wi-Fi consumed 20% more power compared to Bluetooth, and this result closely aligns with the outcomes received by Medel and Brito [10]. The different characteristic features of Wi-Fi Direct and Bluetooth were examined to further compare them to identify which one is better for massive machine-type communication. It was found that Wi-Fi Direct constantly delivered 1.5 to 2 times higher throughput compared to Bluetooth. At the same time, this communication protocol consumed 20-30% more energy during active sessions. These findings align with the data received by the research while testing data transfer using two smartphones. Furthermore, the study by Sauter [8] focused on the examination of Wi-Fi Direct and Bluetooth and highlighted that Bluetooth is most suitable for continuous small data streams. Similar results were achieved by Abiodun [9], who examined Wi-Fi Direct and highlighted its differences from Bluetooth.

Tests performed in the current research indicate that Wi-Fi Direct is suitable for transferring large files, and this finding is supported in empirical studies [8, 11]. Moreover, Sun et al. [11] emphasized that Wi-Fi Direct may be effectively applied for P2P gaming and streaming scenarios. However, complexity in setting up connections is referred to as a disadvantage. This result coincided with the observations of the current study, but the setup complexity is explained by better and faster data sharing. Finally, the research findings confirm that Wi-Fi Direct is associated with high connection success (95%).

Table 5. Summary

Parameter	Empirical Data	Test Results
Speed: Wi-Fi Direct	12-20 MB/s	15 MB/s
Speed: Bluetooth	2-10 MB/s	10 MB/s
Connection Stability	90-96%	95%
Wi-Fi Direct Power	20%	20% compared to Bluetooth

In conclusion, the research findings strongly support the results presented in empirical studies. Bluetooth and Wi-Fi Direct communication technologies provide their users with seamless and reliable data transmission on

smartphones with Android. However, it has been found that they suit different application cases. Hence, Wi-Fi Direct shows the best results for sharing large volumes of data with high speed, but it is associated with high energy consumption (compared to Bluetooth). Bluetooth is energy-efficient and simple. Careful planning and consideration of file size, energy limit, and other characteristic features may help choose the most suitable communication for a certain case.

3.3.3. Study limitations

Although the study focused on the examination of Wi-Fi Direct and its possibility to provide seamless data transfer for Android devices, comparing this technology with Bluetooth, it is associated with several limitations that may affect result generalizability. The first one is a limited device scope. Tests were performed using Google Pixel 4 (Android 12, Snapdragon 955, 6 GB RAM) and Samsung Galaxy S10 (Android 10, Snapdragon 855, 8 GB RAM). The use of more modern devices that support Bluetooth and Wi-Fi Direct may show extended results that represent full performance across the broad range of Android devices. The consideration of other devices indicates that different performance characteristics, including stability, throughput, and power efficiency, may impact results due to antenna quality and system-level optimization.

A controlled environment is another limitation of the study. The testing was performed in a controlled environment that eliminated any interference, which helped isolate wireless protocol performance. Such an environment ensured consistency and fails to represent real-world conditions. Hence, the consideration of environments with different levels of disturbance and high wireless traffic might help learn about data transmission speed and other characteristics. Physical obstacles (other electronic devices in the room or walls), user movement, background applications, concurrent connections, and task prioritization could affect the data transmission process, its quality, and speed.

The next limitation is the size of the transmitted file. It may be beneficial to test the transmission of more file sizes, considering transfer initialization time, error connection, and packet handling efficiency. Hence, a researcher might receive different results, but they could be generalized. Furthermore, constraints associated with power consumption measurement are another research limitation. The researcher relied on the system-level battery use before and after each file transmission to estimate power consumption. Measurement may be insufficient due to various background processes, noise, display activity, and other factors that do not allow isolating energy consumption.

The use of hardware-based power profiling tools may help conduct precise analysis. Small device sample, controlled environment, and limited file size should be interpreted with caution to provide extended information on the Wi-Fi Direct and Bluetooth benefits and drawbacks. Further research should be conducted on different devices, varied file sizes, and dynamic network conditions. Therefore, it is recommended to provide an insight into the performance of Bluetooth and Wi-Fi Direct in real-world settings.

4. Conclusions

4.1. Key findings

The research aimed to evaluate and compare performance characteristics of Wi-Fi Direct while comparing them with similar Bluetooth features in Android. The primary focus was made on data transmission speed, setup complexity, connection stability and reliability, as well as energy consumption. Controlled testing using two smartphones with Android (Google Pixel 4 and Samsung Galaxy S10) assisted in receiving results to inform the practical use of these communication protocols and future research.

The study results indicate that the use of Wi-Fi Direct has more benefits in contrast to Bluetooth applications in terms of data transfer speed, as the testing revealed that the average data transfer rate of Wi-Fi Direct was 15 MB/s, while it was only 10 MB/s for Bluetooth. This implies that Wi-Fi Direct is more suitable for large file transmission compared to Bluetooth.

Moreover, Wi-Fi Direct showed better connection stability, and the repeated transmission sessions helped reveal a 95% connection reliability rate. However, the Bluetooth application experiences some insignificant interruptions and higher signal strength variability. Users who prioritize remote device control, online mobile gaming, and large file transfer value stability and speed.

Bluetooth compromises these advantages compared to Wi-Fi Direct, which demonstrates 20% higher energy consumption but better performance in terms of speed and connectivity. The battery use was monitored while data transmission, and the devices that use Di-Fi Direct show a greater battery drain. The application that requires energy-constrained hardware, for instance, wearable devices, Wi-Fi Direct use may be challenging due to a higher energy consumption rate. Hence, the current study provides a deep insight into the performance characteristics of Wi-Fi Direct and Bluetooth in Android.

Thus, Wi-Fi Direct is more suitable for users who need reliability and speed, while Bluetooth shows better energy efficiency. Which means that these communication protocols are content-sensitive technologies and their choice depends on the app's and user's requirements.

4.2. Results interpretation

The research findings encourage deeper reflection on the interconnection between practical use and performance. The appropriateness of wireless communication technology depends on performance characteristics and application-specific features, including user needs, conditions of use, device type, and battery constraints. Wi-Fi Direct has shown faster data throughput and more stable connections.

These benefits make this protocol most suitable for users who prioritize speed and uninterrupted and fast data transfer. This is attractive for individuals who want to share large files (P2P without internet access) and software, and videos directly between devices. However, it is essential to consider the 20% energy use increase, as some devices operate within limited power budgets. Therefore, battery life is a critical aspect for some users. Bluetooth remains a more suitable option for cases that need continuous communication with modest data volume (data from smartwatches). Low energy consumption makes this communication technology suitable for wearables and IoT contexts.

The research results indicate that neither Wi-Fi Direct nor Bluetooth is a universally ideal option for all Android devices. It is essential to evaluate the technological environment, consider user priorities, analyze device capabilities, and think about user expectations. Connection quality and speed required for short-burst data transfer and high-performance data sharing, Wi-Fi is the best choice.

However, research results indicate that energy performance is dynamic, and it is possible to manage it to some extent, eliminating its negative impact. For instance, the combination of both communication protocols can ensure the achievement of better results, meeting the needs of users and their devices, irrespective of the fact that both technologies are capable of ensuring seamless communication. The interpretation of the study results highlights the importance of optimization, flexibility, and adaptability of wireless communication systems.

4.3. Significance

The research implications extend beyond theoretical and practical application. Android undergoes the process of constant development and improvement, dominating the global mobile market. Therefore, developers and manufacturers make numerous attempts to make changes to meet the continuously evolving needs of modern consumers, improving application functionality, ensuring seamless communication support, and device interoperability.

High-speed P2P communication is the most compelling use case for the analyzed protocols. The use of multiplayer mobile games, mobile file-sharing tools, and offline collaboration platforms offers numerous benefits from using Wi-Fi Direct, ensuring reliable connectivity and the possibility of seamlessly transferring

data. Its stability provides users with engaging experiences that have no space for failed transfers. Therefore, users have an opportunity to share videos and large files without data loss and disruption risks.

Furthermore, Wi-Fi Direct is independent of access points and internet connectivity, which makes it a suitable protocol for decentralized environments. Hence, it may be effectively applied in multiple settings and fields, including education, fieldwork, disaster response, remote work, and many others that have limited or no internet access. This communication technology enables forming localized networks dynamically.

However, developers should consider the battery impact that may distract some users, offering new solutions or options to ensure that devices with a limited battery amount can rely on Wi-Fi Direct in any environment. The research findings provide valuable information to hardware manufacturers as they get extended data suitable for developing or improving device optimization strategies. A deep insight into the technological performance of Wi-Fi Direct may assist in guiding informed decisions regarding the use of sophisticated power-saving algorithms, battery size, and other features.

In the areas of software development, the received findings encourage the development of improved communication models that leverage the challenges associated with Wi-Fi Direct use and consider a smooth combination of Wi-Fi Direct and Bluetooth in devices with Android. The consideration of consumers' needs suggests increased focus on power-saving modes and seamless performance. Thus, the current research is scientifically significant as it provides extended information to guide decision-making in the development of Android applications and hardware integration. Finally, Wi-Fi Direct is a unique communication protocol that enhances P2P experiences.

4.4. Future research

The research provides a solid theoretical base that enhances comprehension of Wi-Fi Direct and Bluetooth, with several limitations that have not significantly hindered the study results. As the testing was performed in a controlled environment, it would be beneficial to test these devices and communication technologies in an uncontrolled setting. This will allow us to learn about the potential complexities of implementing Wi-Fi Direct in real-world applications, the interaction with Bluetooth, and other device groups.

Further research should also test various scenarios of protocol use, examining the change of speed, connection stability, energy consumption, and data transfer quality when a user connects several devices simultaneously. It would be beneficial to evaluate the performance features of Wi-Fi Direct under disturbances and environmental constraints, including other wireless signals, walls, technical appliances like microwaves, IoT devices, and others. Moreover, it is necessary to consider hardware diversity, limitations of Android devices, antenna design, battery capacity, and many other relevant characteristics that may impact connectivity, stability, and speed of data transfer using Wi-Fi Direct and Bluetooth. This may assist developers in better targeting people's needs and providing optimal performance across user settings and demographics.

Moreover, it may be effective to examine Wi-Fi Direct use in environments that operate with Linux or Windows devices. It will help target a wider audience range, focusing on multiple communication platform options, emphasizing their integration and compatibility. Empirical data indicate that it may be beneficial to use both communication protocols, Wi-Fi Direct and Bluetooth, simultaneously to achieve better performance results. Therefore, future research may shed light on the hybrid use of these technologies.

In conclusion, evidence presented in the current research confirms that the beneficial use of Wi-Fi Direct offers advantages of Bluetooth in terms of connection stability and the possibility to transfer high-volume files, even if it consumes more energy. The research results (testing and empirical data findings) confirm that Wi-Fi Direct outperforms Bluetooth.

The findings' implications are significant for users, developers, hardware designers, and scientists interested in the relevant topics within the Android ecosystem. However, it is evident that no technology is universally suitable for all cases. Therefore, the effectiveness of a communication technology directly relates to the

environment, consumers' preferences and needs, contextual appropriateness, system constraints, and raw performance. Thus, future research goes outside controlled settings and examines other potential features of Wi-Fi Direct and Bluetooth to support the new generation of Android devices.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

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