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Smartphone-Centric Wi-Fi Device-to-Device Sensor Communication for User Mobility in AAL Services

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Abstract—This paper evaluates a use-case for smartphone-centric Wi-Fi device-to-device sensor communication that enables user mobility in ambient assisted living (AAL) services. A real-time performance measurement method has been developed and implemented to evaluate the smartphone’s ability to act as a hub and gateway for Wi-Fi connected sensor nodes. The results show that Wi-Fi Direct and Wi-Fi Hotspot are feasible solutions for smartphone-centric device-to-device communication that enables user mobility. In addition, a cloud-based web application for monitoring and displaying sensor data has been implemented.

Keywords—wireless local area networks, device-to-device communication, mobility, ambient assisted living

I. INTRODUCTION

The reasons for the increasing interest in ambient assisted living applications are twofold; the well-known demographic shift with growing share of elderly in the population, and the rapid development of wirelessly connected embedded sensor devices in combination with efficient IT and storage infrastructures. One definition of ambient assisted living is given by Kung and Jean-Bart [1]: “intelligent systems that will assist elderly individuals for a better, healthier and safer life in the preferred living environment and covers concepts, products and services that interlink and improve new technologies and the social environment”. The European initiative Active and Assisted Living Joint Programme (AAL JP) supports applied research on ICT-enhanced services for ageing [2]. EIT Health is another European project for active ageing [3]. The European COST action IC1303 Algorithms, Architectures and Platforms for Enhanced Living Environments (AAPELE) is a third example of research in this field.

Focus for the research on ambient assisted living has been technical systems, infrastructures and services to support elderly people in their daily routine, to allow an independent and safe lifestyle as long as possible, via the seamless integration of information and communication technologies within homes and residences. The ubiquitous wireless local area network standard and de-facto standards (IEEE 802.11 and Wi-Fi Alliance specifications) have enabled mobility within the home. This paper aims at extending mobility outside the home.

The advances in Wi-Fi device-to-device communication mean that smartphone-centric Wi-Fi sensor applications can not only benefit from the mature and ubiquitous Wi-Fi net-

work technology [4], in addition the user mobility will be extended and facilitated as well. Wi-Fi device-to-device communication does not depend on a network infrastructure of existing access points. In this paper we evaluate the performance of smartphone-centric Wi-Fi device-to-device communication for an ambient-assisted living mobility use-case.

Wi-Fi devices, such as smartphones, have the ability to act as software-enabled access points (soft-APs). Most smartphones can be configured as Wi-Fi Hotspots (also called Wi-Fi tethering or portable hotspots) that allow Internet connection. Wi-Fi Direct [5] is a specification from Wi-Fi Alliance where Wi-Fi devices take the role as a soft-AP or a Wi-Fi client. Wi-Fi Aware [6] is another related specification from Wi-Fi Alliance to discover other devices and services within range.

Device-to-device communication is also defined for direct communication between mobile terminals in cellular networks. LTE Direct is an emerging field in cellular communication as a way to off-load traffic in mobile cellular networks. Device-to-device communication can either be in-band (sharing the licensed frequency band for LTE) or out-band (unlicensed frequency bands as Bluetooth and Wi-Fi) ([7], [8]). Device-to-device communication is also considered to be an important component of the emerging 5G architecture [9].

This paper aims at evaluating the hypothesis that Wi-Fi communication is a feasible alternative for smartphone-centric AAL services that allow user mobility outside their homes. The primary target is not applications with very low duty-cycles and very low energy consumption for which ZigBee/IEEE802.15.4, Thread [10] and Bluetooth LE (low energy) [11] are better suited. ZigBee/IEEE802.15.4 and Bluetooth and have been evaluated in our previous research (e.g. in [16] and [23]). The paper presents a use-case with three external wearable sensors (a camera, an accelerometer and an ECG) in Section II, a testbed and measurement method in Section III, and results and analysis in Section IV and Section V.

II. DEVICE-TO-DEVICE COMMUNICATION AND USER MOBILITY

Soft-AP is a way for devices to communicate without an existing wireless local area network infrastructure. It means that other devices than specially designed APs can act as access points for wireless stations. Smartphones can be config-

ured as soft-APs in different ways; as a Wi-Fi Hotspot that provides wireless access to the Internet to other devices; or, using the protocol Wi-Fi Direct [5] specified by the Wi-Fi Alliance. Wi-Fi Direct allows a device to dynamically act as an access point or as a wireless client. In this paper these two alternatives for device-to-device communication are evaluated for a use-case described in Section II.A.

A. A Mobility Use-Case for Ambient Assisted Living

The aim of this use-case is to illustrate user mobility for elderly wearing wirelessly connected sensors. Grandmother Eva is 81 years old. Every day she takes the walker to the local store around 1.5 km from home. She has Type 2 diabetes and went through a by-pass heart surgery less than one year ago. She takes multiple medicines in order to keep the blood sugar level and blood pressure under control. The local healthcare provider has equipped her with an activity sensor, worn in the belt, to monitor and motivate physical activity. The activity sensor is used for fall detection as well. She is also wearing an ECG for long-term heart monitoring. The walker is equipped with a web camera [12] connected to the healthcare provider. The camera and video stream can be activated manually by the user or automatically based analysis of sensor data. Staying at home these devices are connected to a cloud service through the existing Wi-Fi infrastructure and a home gateway. Leaving the home, the devices are connected to the cloud service via the smartphone (Fig. 1). A healthcare provider can display and monitor the devices and the patient in a web application.

In Section II.B two different solutions for Wi-Fi device-to-device communication are described for this mobility use-case.

Fig. 1. A smartphone acts as a hub and a gateway for an IMU, an ECG and a web camera. The smartphone connects the devices to a cloud service that can be displayed in a web application (lower left part) and monitored by a healthcare provider.

B. Wi-Fi Direct and Wi-Fi Hotspot

Wi-Fi Direct is based on the same family of IEEE 802.11 standards as other Wi-Fi networks. The Wi-Fi Direct devices may use IEEE 802.11 a, g or n. In a Wi-Fi Direct connection between a smartphone and external sensors one of the devices (preferably the smartphone) will act as a peer-to-peer group owner (P2P GO) using Wi-Fi protected setup to negotiate a

secure key. The P2P GO is a software enabled access point (soft-AP). It is required to run the Dynamic host configuration protocol (DHCP) to supply the P2P Clients with IP addresses. As mention in [5], a P2P GO may provide Internet access to the P2P Clients) using NAT.

A P2P GO announces itself through beacons in the same way as a traditional access point. After a discovery phase a P2P group can be formed through a negotiation procedure (standard case), with one of the devices as predefined group owner (autonomous case), or a simplified negotiation where any of the devices may act as group owner (persistent case) [5]. Wi-Fi Alliance has introduced Wi-Fi Direct Services (WFDS) in order to enables services as printing, displaying, transmitting and playing across devices from different vendors [13]. Similar to Bluetooth, a Wi-Fi device can advertise available services through WFDS. Unlike Wi-Fi Direct, a smartphone configured as a Wi-Fi Hotspot will automatically route data from sensors via the cellular networks to the assigned server destination.

III. MEASUREMENT METHOD AND TESTBED

A. Aim

The aim is to evaluate the feasibility of using Wi-Fi device-to device sensor communication with a smartphone as a hub and gateway for a mobility use-case that includes multimedia as well as body-worn vital sign sensors. In addition, a measurement method for real-time performance monitoring is presented.

B. Testbed

Three different sensors are connected to a smartphone in the use-case described in Section II.A; an IMU, an ECG and a video camera. Table I shows the typical packet sizes and sampling frequencies for the respective sensors. A modern IMU has ten degrees of freedom; a three-axis accelerometer, a gyroscope, a magnetometer and an altitude meter. Two bytes are needed for each degree of freedom for the IMU with ten-bit samples, which means that each sample requires 20 byte payload. The sampling rate can vary between 5 Hz and 100 Hz. A 16-bit resolution is sufficient for an ECG and the sampling frequency ranges from 75 Hz to 360 Hz. Data output from a web camera can vary a lot depending on the image resolution and frame rate. The Axis M1031 web camera [14] in the testbed transmits 2 Mbyte per second (2000 byte UDP packets every millisecond), which exceeds the bitrate available in Bluetooth LE or ZigBee/IEEE802.15.4.

TABLE I. TYPICAL PACKET SIZES AND SAMPLING FREQUENCIES FOR AN IMU, AN ECG AND A WEB CAMERA

	Packet size (byte)	Frequency (Hz)
IMU	20	5-100
ECG	1	75-360
Web camera	2000	100-1000

The packet sizes and packet frequencies are varied during the tests. Packet delay variation, packet loss, throughput and connection set-up time are measured in two cases where a smartphone acts as a software enabled access point. In the first case, the smartphone is configured as a portable wireless hotspot connected to the cellular network with Internet sharing. In the second case, the smartphone acts as a peer-to-peer group owner (P2P GO) and the sensor nodes act as Wi-Fi Direct peer-to-peer clients. Texas Instrument's Wi-Fi boards CC3200 as well as embedded sensors in smartphones are part of the testbed. Nexus 5X running latest version of Android (Marshmallow) and an iPhone 5S running iOS 9 were used in the measurements. Three Samsung Galaxy S3 running Android (Ice Cream Sandwich) emulate wireless sensors in the performance tests.

In the two dominating operating systems, Android and iOS, smartphones can be configured as portable (personal) hotspots (tethering) and act as wireless access points. Wi-Fi Direct is however only supported in Android. Another limitation is that IP forwarding is not enabled in Wi-Fi Direct for Android, which therefore lacks an embedded solution to route and forward sensor data received by the smartphone to an external server destination. Today, a third-party mobile application for routing is therefore needed.

C. Parameters and Measurement Method

To evaluate the mobility use-case in Section II.A several parameters were measured. The connection set-up time is defined as the time from the initial request until the device has received an IP address and can transmit the first data packet to an external cloud-based server. The response time is defined as the round-trip time (RTT); the time from a packet is transmitted from the Wi-Fi device until the device has received a response from the cloud-based server. The number of lost packets, packet loss ratio and throughput are measured as well. These parameters were estimated in repeated tests for the two different cases, Wi-Fi Direct and Wi-Fi Hotspot. Each test was performed 30 times with 1000 packet transmitted each time. The confidence level for the confidence intervals indicated in Fig. 3 - Fig. 5 is 0.95.

The applied online measurement method [16] combines active and passive techniques. A light-weight performance meter is implemented in the smartphone and each of the sensor nodes. The meter consists of two counters that keep track of the number of sent and received packets and bytes, and a function that can inject monitoring packets. These dedicated measurement packets are inserted between blocks of ordinary data packets as seen in Fig. 2. They contain a sequence number, a timestamp and the cumulative number of packets and bytes transmitted from the sending node to the receiving node.

Fig. 2. A monitoring block surrounded by two monitoring packets.

The interval between the monitoring packets is the size of the monitoring block (Fig. 2). When a monitoring packet arrives, the receiving node stores a timestamp and the current

cumulative counter values of the number of received packets and bytes from the sending node. Observe that for n transmitting sensor nodes, the receiving smartphone maintains n separate monitoring functions, one for each transmitting sensor node.

Synchronization of the clocks in the participating nodes is not required. The local timestamps are used to calculate the inter-sending and inter-arrival times between pairs of monitoring packets. The inter-arrival jitter can then be calculated in a similar way as for RTP timestamps [15]. This means that the arrival time variation is estimated based on the monitoring packets, which represent samples of the ordinary data packet inter-arrival variation. Packet loss, on the other hand, is measured passively and directly using the traffic meter counters.

The following metrics can be calculated and estimated based on the collected measurements described in the previous subsection.

- Packet loss ratio: long-term average and average per monitoring block.
- The length of loss and loss-free periods defined as the number of consecutive monitoring blocks with or without losses.
- Inter-arrival jitter, J , is defined as $J=(r_n-r_{n-1})-(s_n-s_{n-1})$, where s is the sending time, r is the receiving time for timestamp sequence numbers n and $n-1$. The monitoring packets provide samples of delay variations.
- Data throughput between sender and receiver can be calculated as a long-term average and also per monitoring block.

The method and system used for these measurements are described in more detail in [16]. The implemented system enables real-time monitoring of the performance of sensor data communication.

IV. RESULTS

In this section measurement results for set-up time, response time, handoff delays, packet loss ratio and delay variation are presented. Implementation issues related to the different operating systems, energy consumption, data rate and range are also discussed.

A. Connection Set-Up and Response Times

Fig. 3 shows the connection setup time and response time for a Wi-Fi device connecting to a mobile phone using Wi-Fi Hotspot and Wi-Fi Direct. The average set-up time for Wi-Fi Hotspot is around five seconds and three seconds for Wi-Fi Direct. The average response time (RTT) around is one second for Wi-Fi Direct and below half a second for Wi-Fi Hotspot. The average handoff transition time for Wi-Fi Hotspot is ten seconds and eight seconds for Wi-Fi Direct. It is shown in [17] that approximately seven seconds is added to the set-up time if the service discovery function also is included in Wi-Fi Direct. The difference in response time between Wi-Fi Direct and Wi-Fi Hotspot is caused by is the extra time the routing application takes in Wi-Fi Direct compared the smartphone vendors' embedded implementation in the operating system. So far, an

embedded solution for Internet connection in Wi-Fi Direct has not been enabled in Android.

Fig. 3. Connection set-up time and response time (RTT) for Wi-Fi Hotspot and Wi-Fi Direct. The confidence intervals for confidence level 0.95 are indicated.

B. Seamless Handoff and Transition Delays

Fig. 3 also shows the transition delays for handoff when a smartphone is disassociated from an access point in infrastructure mode and re-associated to its own Wi-Fi transceiver as a soft-AP, either as a Wi-Fi Direct group owner or as Wi-Fi Hotspot. The Wi-Fi Hotspot uses the same SSID name as the access point in infrastructure mode, which means that a wireless sensor will switch automatically from the access point to the soft-AP as soon as the access point at home is out of range. In Wi-Fi Direct, the sensors and the smartphone form a Wi-Fi Direct group. Data packets are then transmitted via the smartphone to the infrastructure Wi-Fi AP. The handoff time is measured from the time the smartphone is disassociated from the AP in infrastructure mode until the smartphone is connected to a cellular network.

C. Packet Loss Ratio

The packet loss ratio for three external Wi-Fi devices connected to a smartphone using Wi-Fi Direct is shown in Fig. 4, and correspondingly in Fig. 5 where the smartphone acts as a Wi-Fi Hotspot. The smartphone forwards sensor data to a cloud-based server via the 3G network. The Wi-Fi devices transmit the same amount of data with the same packet intervals. The routing is performed by the embedded software and operating system in Wi-Fi Hotspot and by a mobile application in the Wi-Fi Direct case. Fig. 5 shows results for different packet sizes for Wi-Fi Hotspot; 20 byte (red line colour), 200 byte (yellow line colour) and 2000 byte (blue line colour). The packet loss ratio is low and stable for Wi-Fi Hotspot for all packet intervals and packet sizes.

Fig. 4 shows the packet loss ratio for 20 byte packets (blue line colour), 200 byte packets (red line colour), and 2000 byte packet (yellow line colour) in the Wi-Fi Direct case for increasing packet frequency. It can be observed that the packet loss ratio increases as the packet frequency increases. At the same time a rise in packet loss can be noticed for lower packet frequencies and small packet sizes (20 byte).

A monitoring tool (Android Device Monitor) [18] shows that the operating system assigns low priority to the routing process when the packet frequency is low, resulting in buffer

overflow and packet loss. Very high packet frequencies result in high traffic load and increased packet loss ratio. The packet frequency upper limit when packet loss starts to increase depends on the capacity of the smartphone. The packet loss ratio is more or less the same for all tested packet sizes in Wi-Fi Hotspot (Fig. 5). For Wi-Fi Direct (Fig. 4), increased packet frequency for long packets results in high traffic load on the smartphone and increased packet loss. Forwarding and routing implemented on the application level is not as efficient as the corresponding solution for Wi-Fi Hotspot. The increased loss ratio for small packets at low packet frequencies is due to the operating system's policy to assign low priority to less demanding processes.

Fig. 4. Three Wi-Fi devices connected to a smartphone using Wi-Fi Direct transmitting UDP packets of 20 byte, 200 byte and 2000 byte length. The confidence intervals for confidence level 0.95 are indicated.

Fig. 5. Three Wi-Fi devices connected to a smartphone acting as a Wi-Fi Hotspot transmitting UDP packets of 20 byte, 200 byte and 2000 byte length. The confidence intervals for confidence level 0.95 are indicated.

D. Delay Variations

Fig. 6 shows the delay variation for one, two and three wireless sensors connected to an iPhone transmitting 20 byte UDP packets with different packet intervals. The delay variation is around four milliseconds for the highest packet frequencies (packet intervals close to two milliseconds) for one, two or three connected sensors. However, the delay variation is higher (five to ten milliseconds) for the lowest packet frequencies (packet intervals around 80 milliseconds). The delay variation seems to decrease when the packet frequency increases for one (blue line) and two sensor (red line) devices

connected. The behaviour for three connected sensor devices (yellow line) is different. The delay variation increases between 80 milliseconds and 10 milliseconds, and decreases as the packet interval becomes smaller thereafter. The reason for the often unpredictable behaviour in Fig. 6 is, as mentioned earlier, the different priority the operating system assigns to the processes. It is verified by the monitor tool (Instrument) available in Xcode [19]. This further underlines the need for a real-time performance monitoring system.

Fig. 6. The figure shows delay variation for one, two and three Wi-Fi devices connected to a smartphone (iPhone) transmitting UDP packets of 20 byte. The confidence intervals for confidence level 0.95 are indicated.

E. Operating Systems and Implementation Specifics

Table II summarizes the findings regarding Wi-Fi Direct, Wi-Fi Hotspot and Bluetooth LE (version 4.x) for smartphones running Android and iOS. Fields in green colour show that the device-to-device communication technology overall works well for the respective operating system. Yellow fields indicate some limitations and drawbacks, and fields in red colour mean that the technology is not supported at all by the operating system.

Bluetooth Basic Rate (BR) and Enhanced Data Rate (EDR) are well documented and fully supported in Android, whereas Apple's iOS has no public API for versions of Bluetooth prior to version 4.0 (Table II, column 1). On the other hand, Bluetooth LE (Table II, column 2) is well documented and easy to use in iOS but require modifications of the provided code examples to work in Android (such as non-existent call back functions requiring timers).

The third column in Table II means that sensors nodes are connected directly to the infrastructure Wi-Fi access point at home. However, this case does not support user mobility outside the home. The solutions shown in column 4-6 in Table II permit mobility outside the home. The alternative to configure a sensor node as a soft-AP (Table II column 4) is feasible but only for one sensor connected to a smartphone at a time. Currently Wi-Fi Hotspot (Table II, column 5) works well for Android as well as for iOS. For the use-case in this paper Wi-Fi Hotspot in the smartphone is configured in the same way as a Wi-Fi access point at home. The wireless sensors will be able to seamlessly switch between these two access points. To configure the wireless sensors to connect to an access point is however not straight forward. Several solutions are possible (two are mentioned here). Firstly, a method from Texas In-

struments [20] is to let the size of a transmitted UDP packet indicate which access point to connect to. Another solution [21] is that the sensor node initially acts as soft-AP. After being provided with Wi-Fi name and password it can act as a client and connect to an AP. The implementation of Wi-Fi Hotspot differs between iOS and Android. If Wi-Fi Hotspot is enabled in iOS one can still connect the smartphone to a Wi-Fi access point in infrastructure mode. When the iOS device receives a request from a wireless sensor it turns off the connection to the Wi-Fi access point. After the wireless sensor is disconnected the iOS device may re-connect to the AP. In Android, the connection to the Wi-Fi AP is switched off as soon as Wi-Fi Hotspot is enabled. It is however possible to change the programming of the Wi-Fi setup in Android. The last column in Table II shows that Wi-Fi Direct is supported in Android but not in iOS.

TABLE II. THE TABLE SHOWS HOW DIFFERENT DEVICE-TO-DEVICE TECHNOLOGIES WORK IN IOS AND ANDROID OPERATING SYSTEMS. RED: NOT SUPPORTED. GREEN: SUPPORTED. YELLOW: LIMITATIONS.

	Bluetooth	Bluetooth LE	WiFi Infrastructure mode	WiFi Soft-AP with sensor as AP	WiFi Soft-AP with mobile as AP	Wi-Fi Direct
iOS	Not supported.	Supported. API well documented	Not supported for mobility outside the home.	Partly supported. Only one sensor connected.	Supported. Limitations to discover sensors.	Not supported.
Android	Supported. API well documented	Partly supported. API is not correctly documented	Not supported for mobility outside the home.	Partly supported. Only one sensor connected.	Supported. limitation in discovery of wireless sensors	Supported.

F. Energy Consumption Aspects

Energy consumption is generally higher for Wi-Fi devices than Bluetooth devices (especially Bluetooth LE) and ZigBee devices. However, Wi-Fi Direct is also designed for power-saving. Wi-Fi Direct clients can benefit from the legacy power-saving modes in Wi-Fi. Wi-Fi Direct has defined two power-saving protocols: Opportunistic power save and Notice of absence (NoA) [5]. A Wi-Fi soft-AP is required to be continuously active. With NoA, a P2P GO can announce a sleeping period of fixed or adaptive length to save energy. The authors of [5] have shown that it is possible to reduce the energy consumption by a half or a third compared to being continuously active, without loss of throughput. Bluetooth is specifically targeted to operate with low duty-cycles and relatively low sampling rates. Typical examples of the Generic attribute (GATT) profiles are measurements of heart rate, blood pressure and glucose levels [22].

G. Data Rate and Range

According to Wi-Fi Alliance, Wi-Fi Direct is estimated to allow maximum 250 Mbps. The data rate will depend on whether IEEE 802.11 a, g or n is used. The actual throughput will be determined by the quality of the wireless channel and the number of devices that use the channel. Bluetooth EDR allows maximum three Mbps and Bluetooth LE maximum one

Mbps. The distances between Bluetooth BR and EDR devices are normally less than ten meters, while Bluetooth LE and Wi-Fi D2D both allow considerably longer distances (maximum 150 meter according to the specifications for Bluetooth LE).

H. Cloud-Based Web Service for the Mobility Use-Case

The cloud-based web application illustrated in Fig 1 has been implemented and tested as a proof of concept test for the mobility use-case described in Section II.A. The web application in the lower left part of Fig. 1 displays three cloud-based micro services in different frames. The web camera is activated by e.g. a fall detected from the accelerometer data and the video stream is pushed via an http proxy server. The location is displayed using Google maps and the position retrieved from the smartphone's GPS sensor. ECG data is displayed in a Java script application retrieved via a web socket. This system is tested and works well for Wi-Fi Direct as well as for Wi-Fi Hotspot.

V. ANALYSIS AND DISCUSSION

Our tests show that Wi-Fi device-to-device communication between a smartphone and wireless sensors and devices enable mobility. Wi-Fi Direct and Wi-Fi Hotspot are feasible solutions for the use-case scenario described in Section II.A. The smartphone as a hub and gateway for connected sensor devices can provide seamless transition from infrastructure mode to device-to-device mode, low packet loss and low delay variation for the mobility use case. However, the final performance will, as for all wireless systems, be determined by the conditions in the wireless channel and other competing sources and traffic. A drawback for Wi-Fi Direct is the lack of efficient implementation of routing and forwarding from the smartphone to external servers which results in performance impairments. As shown in Table II, Wi-Fi also works in combination with Bluetooth sensors. Furthermore, we observed deteriorated performance for low packet rates from the sensor devices, due to the operating systems' priority policies regarding resource allocation to processes. This often unpredictable performance of the smartphone and varying quality of the wireless channel underline the need for the continuous real-time performance monitoring system presented in the paper. Methods for management and control of the data rate from sensors and frame rate and resolution from the web camera is part of future work. Wi-Fi Direct power-saving capability means for duty-cycles and battery lifetime in Wi-Fi Direct clients is also for further study.

VI. CONCLUSIONS

This paper has evaluated a use-case for smartphone-centric Wi-Fi device-to-device sensor communication that enables user mobility in AAL service. A real-time performance measurement method has been developed and implemented to evaluate the smartphone's ability to act as a hub and gateway for Wi-Fi connected sensor nodes. The results show that Wi-Fi Direct and Wi-Fi Hotspot are feasible solutions for smartphone-centric device-to-device communication that enables user mobility. In addition, a cloud-based web applica-

tion for monitoring and displaying sensor data has been implemented.

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