Energy consumption of IEEE 802.11 connected consumer electronic devices

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***Abstract*—To use a smartphone as a remote controller for consumer electronic devices, the integrated wireless communication interfaces provide access to common network protocols. Especially the IEEE 802.11 protocol family is widely used. On current smartphones this family provides three different modes of operation for different network topologies. Since energy usage is critical in mobile devices, this paper compares the annual energy usage of the infrastructure, adhoc and Wi-Fi Direct mode based on a simple usecase.**

***Index Terms*—802.11, energy comparision, consumer electronics.**

I. Introduction

Over the last years more and more consumer electronic devices come equipped with communication interfaces. This trend stems from the wish to enable services ranging from simple remote control or metering to “smart” devices connected in an “Internet of Things”. This connectivity also enables more complex applications like “Ubiquitous Computing” and “Ambient Intelligence”. To avoid the cost of additional infrastructure, wireless connections are often used. Low power, low bandwidth protocols like 6LoWPAN[1] are designed to keep the power consumption required for data transmissions low. However those protocols are not included in today’s mobile devices like smartphones or tablets. In order to interface those devices with an existing network, gateway devices are necessary.

Another solution would be to use widespread communication interfaces, like “Bluetooth” (IEEE Standard 802.15.1[2]) or “Wi-Fi” (IEEE Standard 802.11[3]). Modern Wi-Fi interfaces provide three modes of operation[1]: Infrastructure, Adhoc and Wi-Fi Direct.

Since mobile devices are battery powered, the added energy usage of the wireless communication should be a s low as possible. Also due to rising energy cost and environmental impact, the energy usage of the complete system should be as low as possible. To this end energy consumption of wireless communications is the topic of research in many research groups. An Overview of the current state and future direction is given in [5]. The focus of this paper is the comparison of the energy usage of the aforementioned three Wi-Fi modes. After constructing a simple usecase a protocol was designed for each mode that aims to minimize energy consumption while meeting a set of criteria. Power measurements were taken for each component of the network. The paper ends with a conclusion and possible further optimizations.

II. Usecase

Consumer electronic devices spend most of their time waiting to be interacted with. This holds true for more complex devices like a TV-Set waiting for commands from a remote, to simpler devices like an electronic door lock. The lamps used in internal lighting are also switched very rarely throughout the day. For those kind of devices the power consumption in an ”Idle” or ”Sleep” mode is very important.

Measurements taken in [6] and [7] indicate that the energy usage during a ”Receive” state (Wi-Fi transceiver is ready to receive data) is significantly higher than during ”Sleep” state. The better energy management of infrastructure networks should therefore result in a lower usage in this mode.

In order to investigate if this holds still true for modern devices and to include the Wi-Fi Direct mode, a simple usecase was constructed. A typical scenario one encounters in a home automation environment is the control of interior lighting. In this scenario a low energy consumption of the controlling unit is paramount, since potential consumers are used to a very low power control unit - a simple switch. Considering a users expectation, a low delay between actuation and the reaction of the light is also important.To provide an added value to a smartphone controllable lamp, the light color and the brightness can be controlled. Also the temperature of the heat-sink is communicated back to the smartphone.

For comparability of the results a set of frame conditions that are common to all experiments was derived from the described scenario: Since the lamp will only be interacted with when the controller (the smartphone) is in communication range (chosen to 8 h per day), the lamp should be sleeping most of the time. After entering the communication range the initial discovery time should be no more then 10 s. The maximum acceptable delay to switch the lamp was chosen to be 1 s.

[1]The 802.11 standard defines two modes of operation, IBSS - commonly referred to as Adhoc mode and BSS or infrastructure mode. Wi-Fi Direct, developed by the Wi-Fi Alliance [4], uses an infrastructure type network network for peer to peer connectivity.

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III. Test setup

To test the energy consumption under realistic conditions, a demonstrator was built as a platform for the measurements. As an interface to the lamp the Arduino compatible RedFly-Shield, was selected. This extension board uses a RS9110-N-11-02 Wi-Fi chip from Redpine-Signals, that supports 802.11b,g infrastructure and adhoc mode. A microcontroller handles the communication and the control of LED drivers connected to high power LEDs. A Samsung Galaxy-Nexus smartphone with a Broadcom BCM 4330 Wi-Fi transceiver served as a controller. Since the stock firmware does not support the adhoc mode, a custom firmware, CyanogenMod[8], had to be used. The infrastructure network was provided by a RT-N66U access point from ASUS that allows access to most of its 802.11 parameters.

To measure the power consumption of the Wi-Fi interface of the lamp a shunt resistor was placed in series with the extension board. A differential amplifier and an oscilloscope was used to measure the current flowing through the resistor. The power consumption of the AP was measured with a current meter after the power supply. The voltage was assumed to be constant in all cases.

The power consumption for the Wi-Fi transceiver in the smartphone was measured using the battery supply meter included in the phone. To exclude the other components, a reference measurement was taken with a fully charged battery. After approximately one day the power usage could be derived from the battery drain. Consecutive measurements ware taken with the same phone and a fully charged battery and the baseline subtracted from the overall consumption.

IV. Protocols

The application protocol was sent over UDP/IP broadcast packets sent over 802.11 in the various modes at 1 Mbps datarate. In the messages a specific lamp can be addressed as well as every lamp in range. Via a set "Acknowledge" bit the confirmation of successful reception can be required. An additional byte defines the instructions for the lamp like turn on, turn off, send temperature, etc.

In the defined usecase there are three states for the network (see fig. 1 and fig. 2: Smartphone is in range (state 1 and 2) and smartphone is not in range (state 3). To further improve the reactivity of the application the transceiver is not put to sleep if the application is running (state2). As the time spent in this state is very short only 1 and 3 were considered for the overall energy consumption. The adhoc and the Wi-Fi Direct mode required slight adjustments.

A. Adhoc

The adhoc implementation on the Galaxy Nexus and on the Wi-Fi extensionboard did not support the power save modes based on ATIM-frames specified in the 802.11 standard. Therefore the power management was done on the application layer mimicking the DTIM-frames in an infrastructure network. Figure 1 shows this process in state 1. The application on the smartphone uses another byte in the application protocol to tell the microcontroller on the lamp after which interval the next packet, if data needs to be sent, is to be expected. After the reception of such a DTIM'-packet, the microcontroller puts the transceiver to sleep until the interval, minus a safety margin, has passed. The transceiver needs to disconnect from the network before going to sleep and needs to scan and join the network after waking up. This process plus receiving the DTIM'-packet (T_active') takes approx. 500 ms. Compared to the time needed in infrastucture and Wi-Fi Direct (T_active see next section) mode this value is much higher and therefore not equivalent to a built in energy management.

If the smartphone is not within range of the receiver the lamp scans for a controller with the interval 10 s (T_Scan). The channel for the network is assumed to be fixed so only one channel has to be scanned which takes 154 ms. In between scans the transceiver is put to sleep.

B. Wi-Fi Direct

In Wi-Fi direct mode the smartphone creates an infrastructure network which the lamp can join. A WPA2 passphrase is created when the network is started for the first time. Part of the SSID of the network is randomly generated when the network is started for the first time. Both values were hardcoded in the firmware of the receiver.

When the smartphone is in range of the lamp and the network is started, the power management based on DTIM-frames can be utilized (shown in fig. 2 State 1). The time T_active in which the receiver needs to be active to receive a message is 5-7 ms.

After an IDLE period in which no DTIM-frame was received, the receiver assumes the controller is out of range (state 3). In contrast to adhoc and infrastructure mode the Wi-Fi channel is not fixed. This means, that the receiver in the lamp needs to scan every channel for the presence of the network if the smartphone is not in range. With 1473 ms this takes significantly longer than in an adhoc network. The time between scans (T_Scan) was set to 10 s.

V. Results

Using the previously described test setup and algorithms, several test were run to determine the energy usage of the individual components. Independent from the Wi-Fi modes, the Wi-Fi extension board drew 637 mW of power while receiving. In sleeping mode the power consumption was 43 mW. Since a lamp is not switched several times per minute, the additional energy required for sending was neglected in the calculations (In the sending state the transmitter used 1442 mW with highest sending power).The following sections show the results for the different modes.

A. Infrastructure

Using the previously mentioned access point, the smartphone and the lamp were connected to an infrastructure network. To have minimum interference with surrounding networks the channel was set to 8 in the 2.4 GHz band. The beacon interval was at 100 ms and the DTIM interval set to

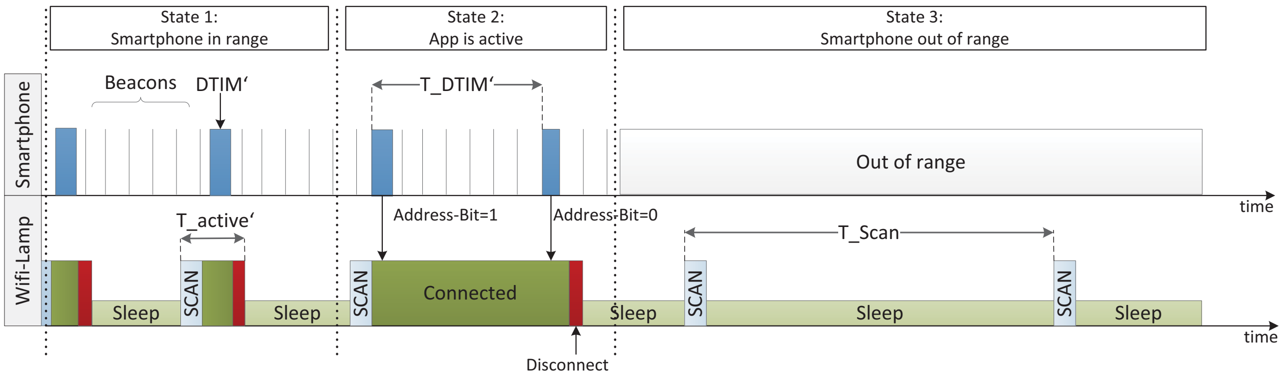

Fig. 1. Sequence diagram for the adhoc mode. The smartphone is either in range (State 1) with the controlling application running (State 2) or it is out of range from the receiver (State 3). The sent and received network frames are displayed for the smartphone and the lamp.

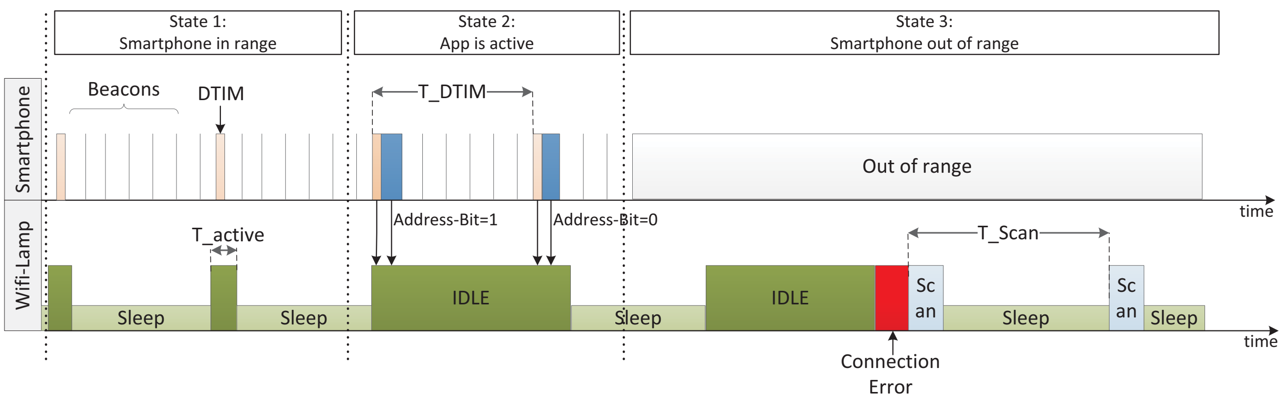

Fig. 2. Sequence diagram for the Wi-Fi Direct mode. The smartphone is either in range (State 1) with the controlling application running (State 2) or it is out of range from the receiver (State 3). The sent and received network frames are displayed for the smartphone and the lamp.

300 ms (To be comparable to adhoc and Wi-Fi direct mode). Table I shows the results for the lamp, the smartphone and the access point.

TABLE I
ENERGY CONSUMPTION IN THE INFRASTRUCTURE MODE.

	Power[mW]
Wi-Fi-lamp	46.3
Access point	7430
Smartphone	156,9

The smartphone and the lamp show the best result for the energy consumption in this mode. This can be attributed to the power management in infrastructure networks. Since the devices are assumed to be always connected, they don't waste power scanning for the network. The savings on the device side come with the high cost of having an additional device which power consumption is quite high at 7.4 W. Since an access point also serves other devices its power consumption can not be attributed solely to the controlling of the lamp, we decided not to include it in the figures for the result.

B. Adhoc

For the adhoc measurements the network was created on channel 8 in the 2.4 GHz band. Since the used Galaxy Nexus did not support this mode directly it was not (yet) possible to influence beacon intervals (fixed at 100 ms) or to enable power management functions. The results for the measurements are displayed in table II.

TABLE II
ENERGY CONSUMPTION IN THE ADHOC MODE.

	Power[mW]
Scan [mWs]	149
SP out of range	56.9
SP in range	349
Smartphone	370

In this network mode the smartphone draws the highest amount of power. This might be due to the unsupported mode of operation and the unsupported power management features.

Due to the more efficient scanning the consumption in the "out of range" case is less than with Wi-Fi direct. However in the "in range" case the consumption is significantly higher. This is a direct result of the much longer T_active time due to the application level power management.

C. Wi-Fi Direct

The Wi-Fi Direct mode on the smartphone is well supported within the API of Android. However besides creating and scanning for networks the parameters on the physical layer could not be influenced. The channel was chosen randomly and the beacon rate (100 ms) and the DTIM-interval (300 ms) could not be changed. Table III shows the results for the measurements.

TABLE III
ENERGY CONSUMPTION IN THE WI-FI-DIRECT MODE.

	Power[mW]
Scan [mWs]	937.9
SP out of range	130.5
SP in range	53.9
Smartphone	316

The energy consumption for the receiver in the "in range" state in this mode is comparable to the infrastructure mode. In the "out of range" case the consumption is much higher than in the adhoc mode. This is due to the higher energy demand for a scan of all channels. Since the smartphone replaces the access point in this mode, the power consumption is also higher than in an infrastructure network.

D. Summary

In conjunction with the previously defined frame condition an annual energy consumption can be estimated. Table IV shows the consumption for the different modes and individual devices.

TABLE IV
ANNUAL ENERGY CONSUMPTION FOR THE COMPONENTS IN KWH.

	Infrastucture	Adhoc	Wi-Fi direct
Lamp Wi-Fi	0.405	1.367	0.912
Smartphone Wi-Fi	0.458	1.08	0.922
Access Point	*65*	-	-
Overall	0.86	2.45	1.83

The values in Table IV were estimated with a DTIM-interval of 1000 ms. This basically directly translates to the maximum delay between a keypress on the controller and a reaction of the lamp (plus processing delay. If a longer delay is acceptable, the application level power management in the adhoc mode should yield better results due to the high overhead of T_active'. This behavior is shown in fig. 3.

The ratio between "in range" and "out of range" also influences the energy consumption. Fig. 4 shows the annual consumption for different "in range" times. The better energy consumption in the adhoc mode when the smartphone is not in range of the lamp, causes the adhoc mode to perform better

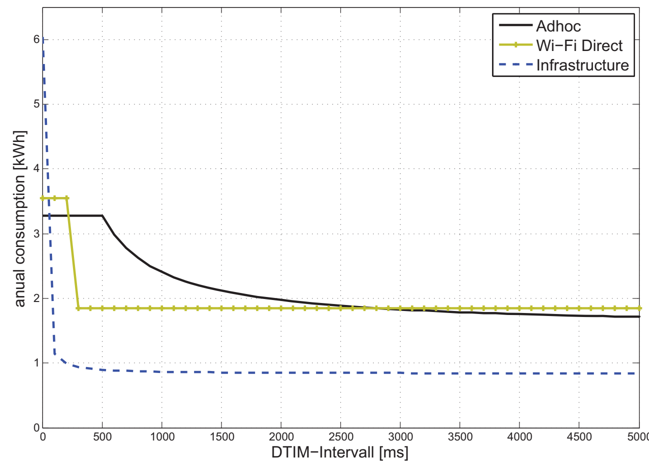

Fig. 3. Anual power consumtion (smartphone and transceiver) over the DTIM-intervall. The interval at Wi-Fi Direct (300 ms) could not be changed.

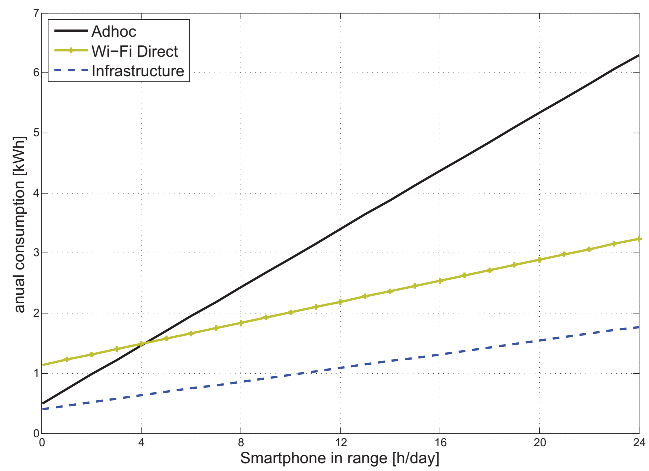

Fig. 4. Anual consumption (smartphone and transceiver) over the time in which the smartphone is in range of the receiver. The consumption of the lamp in infrastructure mode is constant because it is assumed to be always connected. Only the consumption of the smartphone rises with the active time.

than the Wi-Fi Direct when the phone is in range less than 4 h/day.

VI. CONCLUSION AND FUTURE WORK

To use a smartphone as a remote controller for a LED based lamp, Wi-Fi as a common communication protocol can be used. The Wi-Fi standard provides three modes for different network topologies. To compare the energy usage of each mode, a usecase was constructed from which a set of common criteria was derived. On this basis different algorithms were implemented on the smartphone and the Wi-Fi interface of the lamp to use as little energy as possible while maintaining the defined criteria. For each mode energy measurements were conducted to calculate an annual consumption.

The results from the measurements show that out of the 3 Wi-Fi modes, the infrastructure mode uses the least amount of energy for the given usecase. If the energy required to operate the access point is taken into account, Wi-Fi Direct uses only 2.7% of the annual energy. Considering a scenario with multiple lamps, the energy usage per device in adhoc mode will be less than the measured values, due to the distributed beaconing in adhoc networks.

The power consumption of modern Wi-Fi transceivers has improved significantly compared to the results presented in [6] which measured the idle consumption with approx. 850 mW (DSSS Lucent IEEE 802.11 WaveLAN PC Bronze @2Mbps). The Galaxy Nexus smartphone drew 370 mW on average including the beacons for the adhoc network.

As a basis for the software the default Wi-Fi drivers on the smartphone and the interface of the lamp were used. Since neither supported the ATIM power management of the adhoc mode a implementation of this functionality would yield better results for this mode. As future work additional power saving algorithms as proposed in e.g. [9] for Wi-Fi Direct could be implemented. Also a comparison to commercial systems like the Philips Hue lamp and low power communications protocols in conjunction with gateway devices could provide further insight into the energy usage for the wireless connectivity of consumer electronic devices.

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