PROCEDURE FOR ASSESSMENT OF GENERAL PUBLIC EXPOSURE FROM WLAN IN OFFICES AND IN WIRELESS SENSOR NETWORK TESTBED

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Abstract- **A fast and accurate measurement procedure to determine experimentally WLAN radiofrequency (RF) exposure and to test compliance with international guidelines for the general public, is proposed. This is the first paper where all optimal settings for the measurement equipment (sweep time, resolution bandwidth, etc.) are investigated, selected, and validated. The exposure to WLAN access points is determined for 222 locations with 7 WLAN networks present in office environments. The WLAN exposure is also characterized for the first time in a Wireless sensor lab environment (WiLab) at IBBT-Ghent University in Belgium. Average background exposure to**

WLAN (WiLab off) is 0.12 V/m, with a 95th percentile of 0.90 V/m. With the WiLab in operation, average exposure increases to 1.9 V/m, with a 95th percentile of 4.7 V/m. All values are well below the ICNIRP guidelines of 61 V/m in the 2.4 GHz band (at least 9.1 times for distances of more than 1 m from the access points) but a significant increase of exposure is possible in wireless sensor labs due to high duty cycles. By applying the proposed measurement method a relevant reduction in measurement time is obtained.

***Key Words*- RF, WLAN, exposure of general public, measurement, Wi-Fi, wireless sensor lab.**

I. INTRODUCTION

In current office buildings, wireless local area networks (WLANs) are common technology. People spend a large amount of their time in the office during working hours and are thus exposed to these WLANs. In addition, wireless sensor testbeds are already in use by a lot of research institutions worldwide in order to effectively test the wireless protocols or applications in a real-life environment (e.g., WiLab: http://wilab.test/index.php, Motelab: http://motelab.eecs.harvard.edu). Some testbeds have been deployed in real *office-like* buildings (Werner-Allen et al. 2005, Handziski et al. 2006) and others in real office buildings (e.g., http://wilab.test/index.php). Exposure due to WLANs using Wi-Fi technology is only rarely investigated (and never in wireless sensor testbeds) and the correct measurement of the WLAN exposure to test compliance with safety standards such as ICNIRP 1998, IEEE C95.1 2005, and FCC 2001, has rarely been studied.

Foster 2007 investigated exposure of Wi-Fi access points for 55 sites during a period of 40 to 120 s. No attempt was made to measure 6- or 30-minutes exposures. In all cases, the measured Wi-Fi signal levels were below international exposure limits (ICNIRP 1998, IEEE

C95.1-2005, FCC 2001) (Foster 2007). Also Kühn et al. 2005, 2007 and Neubauer et al. 2005 investigated short-period (maximal) exposure due to Wi-Fi access points. Myhr 2004 and Hamnerius 2005 assessed exposure of WLAN for 46 positions. Myhr 2004 reported that the maximum measured average power density was 1.72 mW/m^2, a value approximately 6000 times lower than the ICNIRP guidelines (ICNIRP 1998). In Hamnerius 2005, only a limited number of settings is provided and it is stated that the combination of a measurement antenna and a spectrum analyzer can be used for exposure assessment. G. Schmid et al. 2007 investigated typical WLAN exposure for different scenarios and found that the maximum temporal peak values of power density, spatially averaged over body dimensions, were found to be lower than 20 mW/m^2, corresponding to 0.2 % of the reference level according to the European Council Recommendation 1999/519/EC (ECR 1999). A standard for *in-situ* measurements is developed in CENELEC 2008. Some considerations concerning WLAN and Wi-Fi are mentioned in annex.

This is the first paper where all optimal settings of the measurement equipment (i.e., spectrum analyzer (SA)) used for the (WLAN) exposure assessment are discussed, enabling correct measurements to determine compliance with safety standards. If settings are discussed in literature, almost never all parameters (and certainly not the sweep time) are discussed or only vaguely specified (e.g., in Schmid et al 2007 it is stated to use “sufficient” large sweep times). Here it will be shown that these settings have a huge influence on the measurement results and that it is very important to specify these. A new fast procedure to perform measurements during about 1 minute per orthogonal field component (and 1 minute to monitor the activity of the WLAN channels) and to obtain results that are representative for 6 and 30 minutes exposure is presented. Finally, WLAN exposure is measured on-site and determined for 7

WLAN networks in an office environment at 222 locations (which was possible thanks to the new and fast method) and for the first time to our knowledge, general public exposure in a wireless sensor testbed (named WiLab) is determined. This sensor testbed consists of 200 nodes (equipped with 2 Wi-Fi IEEE 802.11 interfaces (a/b/g) and 1 or 2 sensor nodes with IEEE 802.15.4 interface and with embedded temperature, light and humidity sensors) over 3 floors of an office building. The IEEE 802.11 interfaces have transmitting (and receiving) antennas and each IEEE 802.15.4 interface has an antenna to transmit data from the sensors (e.g., temperature), which causes RF exposure when transmitting.

II. MATERIALS AND METHOD

A. Location of measurements, environment, and WLAN APs

WLAN exposure is determined in an office environment in a modern (4-year old) office building. In this building 7 different Wi-Fi networks are present using IEEE 802.11b and IEEE 802.11g technology (IEEE 802.11b 1999, IEEE 802.11g 1999).

In this building also the wireless sensor testbed WiLab is deployed: it consists of 200 nodes spread over three floors of the 12x90 m^2 office building. The architecture of the testbed is based on the widely used MoteLab testbed concept from Harvard University (http://motelab.eecs.harvard.edu). The nodes (iNodes) are embedded PCs equipped with ethernet, USB, etc., and each node has two 802.11 a/b/g wireless network interfaces (type COMPEX WLM54-SAG23, www.compex.com.sg, COMPEX SYSTEMS PTE LTD. 135 Joo Seng Road #08-01 PM Industrial Building Singapore 368363) with each a 5 dBi antenna.

The exposure for all WLAN networks and the WiLab in the office environment will be assessed. For the development of the measurement procedure, we focus on two types of access points (AP) present in the office building, namely a D-Link AirPlus G+ Wireless Router (802.11b/g, www.dlink.com, D-Link Global Headquarters, No. 289, Sinhu 3rd Rd., Neihu District, Taipei City 114, Taiwan) and a WiLab access point (802.11g, COMPEX WLM54-SAG23). Two modes will be considered: *idle mode* i.e., only beacon packets are transmitted by the AP and broadcast mode i.e., the AP is (almost) transmitting continuously. The D-Link AP will be used in idle mode (with beacons each 1 ms or 100 ms, long preamble). The WiLab AP will be used in broadcast mode with maximal data traffic, in which the normal CSMA/CA protocol (Carrier Sense Multiple Access with Collision Avoidance) is ignored (conservative approach).

B. Procedure and settings to correctly assess Wi-Fi exposure

WLAN signals vary in time. The WLAN packets are transmitted with a minimal duration of 20 μs (i.e., duration of the minimum PLCP (Physical Layer Convergence Procedure) header). The 0-dB bandwidth of the signals is 18 MHz (802.11g) or 22 MHz (802.11b).

If we want to measure exposure due to WLAN with a SA, the maximum-hold mode (noted as *max-hold mode*, and defined here as a measurement of a signal with the maximum-hold setting until the SA reading stabilizes) will have to be used during a certain amount of sweeps. In this way the maximal field value during a measurement time is determined. But because these WLAN signals are not continuously transmitted, the maximal value has to be multiplied with a duty cycle in order to obtain an accurate estimation of the total RMS power density averaged over 6 minutes as proposed by ICNIRP 1998 or 30 minutes as proposed by IEEE C95.1-2005. The total RMS electric field is here noted as E_{tot}^{avg}. Fig. 1 illustrates this principle:

a single sweep of the WLAN signal of the D-Link AP (idle mode) and the WiLab AP in broadcast mode (RBW = 20 MHz, RMS detector, SWT = 2.5 ms) is taken with the SA in zero span mode. For both APs two bursts are shown in Fig. 1. *The total average electric field* E_{tot}^{avg} will be determined using the duty cycle and the power measured during the active duration. Therefore, the following measurement procedure is recommended for WLAN (shown in flow graph of Fig. 2). In a first step, the *active* WLAN channels are determined with a WLAN-packet analyzer. Secondly, the *duty cycle* of the active channels is determined. Thirdly, *max-hold measurements* of the electric field of the different WLAN channels are performed with SA and a tri-axial measurement probe (calibrated during past year). Finally in a fourth step, the *total average electric field* E_{tot}^{avg} is calculated by multiplying the maximum hold value (= average *active* electric field) with the root of the appropriate duty cycle. The different steps of Fig. 2 and settings are now explained below. Table 2 summarizes all settings used for the WLAN assessment**.**

1) *Determination of active channels (Fig. 2)*

We only consider in this paper WLANs using Wi-Fi technology in the 2.4 GHz band (802.11b and 802.11g). The maximum transmit power levels for 802.11b/g meet the requirements of local regulatory bodies (e.g., Equivalent Isotropically Radiated Power EIRP of 100 mW for Europe). Using a Wi-Fi-packet analyzer, the active Wi-Fi channels are determined. The analyzer consisted of the software tool Airmagnet (www.airmagnet.com, 830 E. Arques Ave. Sunnyvale, CA 94085 United States) together with a laptop and a Wi-Fi card of type Proxim ORiNOCO 11 a/b/g Client Combocard gold (www.orinocowireless.com, 1561 Buckeye Drive Milpitas, CA 95035, USA). As an alternative, active channels can also be determined using max-hold measurements with a SA in the frequency domain. Using the packet analyzer software also the burst length of the AP signals can be determined. This length will be important to select optimal settings of the SA in order to perform correct measurements. Table 1 lists the total burst length of the considered D-Link AP (802.11b/g) and WiLab AP (802.11g) signals, together with the characteristics and modes used for these APs. Table 1 also lists the optimal sweep time (SWT), that will be discussed further**.**

The data transmitted using 802.11b/g (802.11b 1999, 802.11g 1999) is encapsulated in different headers. The physical-layer frame is called PPDU (Physical layer convergence Procedure (PLCP) Protocol Data Unit) and consists of a PLCP preamble for synchronization, a PLCP header and a MAC-frame as body. The MAC-frame consists of a header, body and FCS (Frame Check Sequence for error correction of the MAC-frame) with a length of 4 bytes. For *802.11b* two formats are possible, called the long and the short preamble (DSSS, Direct-Sequence Spread Spectrum). The short preamble improves the performance for high data rates with respect to a long preamble. For the long preamble and the PLCP header the length is 144 bits and 48 bits, respectively, and is transmitted at 1 Mbps. For the short preamble, the length is 72 bits (1 Mbps) and the PLCP header is 48 bits (2 Mbps). The total time duration for the long preamble is thus 192 μs (i.e., $\frac{144+48\,bits}{1\,Mbps}$) and for the short preamble is 96 μs (i.e., $\frac{72\,bits}{1\,Mbps}+\frac{48\,bits}{2\,Mbps}$).

The physical layer of *802.11g* is known as ERP (Extended Rate PHY). For 802.11g three formats for the preamble and the header are possible: the short preamble, the long preamble (as for 802.11b), and a preamble and header based on the 802.11a protocol (ERP-OFDM, Orthogonal Frequency Division Multiplexing). The preamble and header based on 802.11a have a duration of 20 μs (802.11g 1999, Myhr 2004).

The duration of the physical frame (or burst length) is thus calculated as follows:

$$physical\ frame\ duration = (preamble + header)\ duration + length\ decoded\ packet/data\ rate + length\ FCS/data\ rate\ [\mu s] \quad (1)$$

With FCS the frame check sequence having a length of 4 bytes. In Table 1, we use for the D-Link (802.11b) AP a preamble of 192 μs long and for the WiLab AP 20 μs (802.11g) long. The data rate for the idle mode is 2 Mbps (D-Link) resulting in the total burst length (i.e., active duration t_{active}) of 568 μs, the data rate for the broadcast mode is 54 Mbps corresponding with a total burst length of 209 μs (Table 1)**.**

2) Duty cycle T (Fig. 2)

The duty cycle T [%] is defined as the ratio of active duration t_{active} [s] to total duration t_{tot} [s] of the WLAN signal:

$$T = 100 \cdot \frac{t_{active}}{t_{tot}}\ [\%] \quad (2)$$

In Fig. 1 we indicated t_{active} and t_{tot} to illustrate the calculation of the duty cycle T. For the active channels the duty cycle is determined with a tri-axial R&S TS-EMF Isotropic Antenna (dynamic range of 1 mV/m – 100 V/m and a frequency range of 30 MHz – 3 GHz) in combination with a spectrum analyzer (SA) of type R&S FSL6 (frequency range of 9 kHz – 6 GHz) (http://www2.rohde-schwarz.com, R&S Belgium, Excelsiorlaan 31 1930 Zaventem Belgium). The tri-axial field probe is connected with the SA with an 8-m coaxial cable in order to minimize the influence of the operator during the measurements.

For the determination of the duty cycle *T* [%], the zero span mode of the SA for the different active channels with center frequency equal to the channel frequency (2412 MHz + 5·k MHz, k = 0, …,12) is used with the settings shown in the first part of Table 2. To obtain these settings, experiments with the D-Link AP in idle mode and the WiLab AP in broadcast mode are performed.

We take different single sweeps and chose the following settings for the estimation of *T* (first part of Table 2): the root-mean-square (RMS) detector, a sweep time (SWT) of 1 ms and a resolution bandwidth (RBW) of 1 MHz.

Due to the stochastic signal characteristics of the WLAN signals an *RMS detector* must be used in order to avoid systematic overestimation of the fields (as in case of using a peak detector) (Schmid et al. 2007).

The *SWT* has to be sufficiently large to measure as many packets as possible in a single sweep but not too large in order to distinguish between individual packets. When SWT is too large, packets cannot be distinguished anymore, if SWT is too small then too many traces are needed to obtain an accurate estimate of *T*. As a compromise we chose SWT equal to 1 ms.

RBW has to be large enough to have smaller variations of the noise floor (variations less for 1 MHz than e.g., for 300 kHz) and to obtain a signal that is high enough above the noise floor to be able to detect it. RBW has to be small enough to avoid large contributions of adjacent channels, which can result in a bad estimation of *T*. We chose thus RBW equal to 1 MHz (Table 2, an extensive explanation about the choice of SWT, RBW and other parameters will be provided in Section II.B.3)).

The *number of single sweeps* required to obtain an accurate estimate of T is equal to 2,200. This number is determined as follows (Fig. 3). First, 100,000 single sweeps (zero span mode) with SWT = 1 ms are measured, resulting in a measurement time of 100 s. Then we define windows of 1, 2, ….100, ….100,000 sweeps (or traces) and calculate the duty cycle for each window. Finally, we determine the optimal number of traces resulting in a relative error of T less than 5 % (with respect to 100,000 sweeps). We estimate T with t_{active} of a WLAN signal in (2), equal to the time that a measured packet is 5 dB above the noise floor (equal to -78 dBm for the settings in Table 2). This is shown in Fig. 3. For a small number of traces, clearly a large variation of the estimation of T can be noticed. But the value of T converges after a certain amount of traces. For the D-Link AP in idle mode with beacon period of 100 ms, T is equal to 0.6 % (this can also be derived from Table 1; t_{active} = 568 μs and the period is 100 ms) and this number of sweeps is equal to 100 (for D-Link with beacon period of 1 ms the number of sweeps is equal to 363), while for the WiLab AP in broadcast mode 2,157 sweeps are required and T = 86 %. Therefore, we recommend in Table 2 measurements consisting of about 2,200 sweeps.

3) *Max-hold measurements in the frequency domain (Fig. 2)*

Max-hold measurements are performed in the frequency domain with the optimal settings listed in the second part of Table 2.

The power of the *active* WLAN signal is measured with the SA (RMS detector and max-hold in frequency domain) and the tri-axial isotropic probe during a period of 1 minute for each vector component until the signal stabilizes. The measured power of each orthogonal component is converted to field values using the antenna factor of the probe [dB(1/m)] and eqns. (4) and (5) of (Joseph et al. 2006). When the three orthogonal magnitudes (E_i, i = 1, 2, 3) are measured, the total active field E_{tot}^{active} is calculated from these three magnitudes ($E_{tot}^{active} = \sqrt{E_1^2 + E_2^2 + E_3^2}$). The measurement uncertainty for the electric field is ± 3 dB for the considered setup (CENELEC 2008). The measurement uncertainties are estimated at the level of twice the standard deviation (corresponding in the case of a normal distribution, to a confidence level of 95 %). The settings that now will be discussed (Table 2) are RBW, SWT, VBW, detector mode, and span.

Resolution bandwidth RBW

Resolution bandwidth is an important setting for the SA (Joseph et al 2008). Fig. 4 shows the power of an 802.11b signal of a D-Link AP (beacon period of 1 ms) measured by the SA for different available RBWs (30 kHz, 300 kHz, 1 MHz, 3 MHz, and 10 MHz). The center frequency (CF) is 2.472 GHz and the SWT is fixed to 10 ms (see next section). Further, the RMS detector is used with a frequency span of 50 MHz. The power and thus the fields for every component are added for each RBW over the WLAN signal bandwidth BW of 20 MHz:

$$E_i = \sqrt{E^2_{(f_0, f_0+RBW),i} + E^2_{(f_0+\delta, f_0+2RBW),i} + ... + E^2_{(f_1-RBW, f_1),i}} \quad [\mathrm{Vm}^{-1}] \qquad (3)$$

With i = 1, 2, 3 (the orthogonal field components E_i), f_0 = CF – BW/2, f_1 = CF + BW/2, BW = 20 MHz, $E_{(f_0, f_0+RBW),i}$ is the field measured by the SA in a band equal to RBW in the interval (f_0, f_0+RBW). Thus the larger RBW, the less terms have to be added in eq. (3).

The measured power for each pixel in Fig. 4 increases clearly for larger RBWs. For a small RBW = 30 kHz, the signal power is not measured correctly because the frequency separation Δf between the frequency points is 110 kHz (span of 50 MHz divided by 455 display points of the SA) and thus larger than the RBW of 30 kHz. Therefore a part of the signal power is lost and too low values are measured with this RBW. To measure correctly the power of the signal, RBW has to be larger than the frequency separation Δf. From an RBW of 300 kHz on, this is fulfilled. The measured power of a component in Fig. 4 for different RBWs, using the summation of (3) is 20.15 dBm for RBW = 300 kHz, 15.90 dBm for RBW = 1 MHz, 16.07 dBm for RBW = 3 MHz, and 16.07 dBm for RBW = 10 MHz. From an RBW of 1 MHz on, the measured power converges to the correct and stable value of 16 dBm. We select then the RBW of 1 MHz (see Table 2) to obtain a correct measurement and still be able to distinguish the different channels and minimize overlap if adjacent channels are present. The larger the RBW, the less different adjacent channels can be distinguished, for RBW = 3 MHz and 10 MHz this is already difficult. Analogous results are obtained for an 802.11g signal.

In Myhr 2004 and Rauscher 2001, RBWs of 1 to 3 % of the channel bandwidth (BW) are recommended in order to distinguish the different channels. This results in about 600 kHz for the WLAN measurements, which might be somewhat low. We recommend an RBW of 1 MHz for the reasons mentioned above.

Sweep time SWT

The sweep time is of enormous importance for SA measurements. Figs. 5 (a) and (b) show the measured power P [dBm] of a component of an 802.11b and 802.11g signal, respectively, measured for SWTs of 2.5 ms, 10 ms, 50 ms, 100 ms, 0.5 s, 1 s, 6 s, and 60 s (for D-Link and WiLab AP) and also a SWT of 5 ms for the 802.11g signal of the WiLab AP. The center frequency is 2472 MHz and 2450 MHz for the D-Link and WiLab AP, respectively and the

RBW is fixed to 1 MHz. Further the RMS detector is used with a frequency span of 50 MHz and the max-hold mode during 1 minute.

The larger the SWT, the lower the measured power P [dBm] (Fig. 5), because the time duration of the RMS value of a pixel on the display is determined over a larger duration: for very large SWT (thus slow measurements), the SA-samples consist of signals measured both during the active and inactive periods of the AP. Therefore, the (active) signal is underestimated if we measure with SWTs that are too large. For very small SWT (fast measurement), the time duration of the display samples is very low, resulting in an overestimation because the WLAN signal is noise-like and the max-hold value is calculated. To perform correct measurements, SWT has to be set in such a way that the inter pixel time *IPT* (i.e., duration of 1 pixel) is equal to the active duration t_{active}. The SWT must be set to get one complete signal period within one pixel on the SA screen during the frequency sweep. The optimal SWT of the SA for the D-Link and the WiLab AP is calculated in Table 1 using (4):

$$SWT = t_{active} \times n \qquad [\mathrm{s}] \tag{4}$$

With n the number of display points of the SA (n = 455 for the considered SA) and t_{active} is the active duration. For the D-Link AP, the ideal inter pixel time is 568 μs as shown in Table 1, resulting in a SWT = 258.4 ms (nearest SA setting is 260 ms), while for the WiLab AP the ideal inter pixel time is 209 μs, resulting in a SWT = 95.1 ms (Table 1, nearest SA setting is 100 ms). If the burst length (i.e., t_{active}) is not known (which is mostly the case if one has to perform exposure measurements), we select SWT in such a way that we do *not underestimate* the exposure (conservative approach): thus SWT is chosen small enough and equal to the lowest duration of t_{active} for the considered WLANs. For the ERP-OFDM header the duration of the active time is *minimal* and equal to 20 μs (802.11b, 802.11g, Myhr 2004). Therefore we obtain using (4), a $SWT = 20 \cdot 10^{-6} \cdot 455 = 9.1$ ms, which is a worst-case value. We select SWT = 10 ms in Table 2 because the nearest SA setting is 10 ms (*IPT* is then 22 μs) for the measurements if the packet length and thus packet duration is not known.

Other settings

In Table 2 also detector mode, video bandwidth (VBW), and frequency span are specified.

Due to the stochastic signal characteristics an *RMS detector* must be used in order to avoid systematic overestimation of the fields (as in case of using a peak detector) (Schmid et al. 2007).

Concerning the *VBW*, CENELEC 2008 recommends that $VBW > 3 \cdot RBW$. When selecting VBWs which are too small, deviations up to 2.5 dB are possible for Gaussian noise (Rauscher 2001) because the VBW is a first-order lowpass configuration and high frequency values are ignored. For a correct power measurement, the SA video signal must *not* be limited in bandwidth. A restricted bandwidth of the logarithmic video signal results in a too low indication of the power. From our WLAN measurements it can be concluded that deviations smaller than 0.76 dB are obtained as long as $VBW \geq RBW$. If $VBW < RBW$ then deviations up to 1.4 dB were registered (RMS values, RMS detector). In Table 2, we propose thus a VBW = 10 MHz, which is sufficiently larger than the RBW of 1 MHz (recommended above) and complies with the requirement of CENELEC 2008.

The *frequency span* is selected in such a way that the bandwidth for each frequency separation between two pixels (Δf) is smaller than RBW (thus $\Delta f < RBW$) because otherwise only part of the signal is measured (by the RBW) and underestimation is possible. The influence of the selected span is limited: maximal deviations of only 0.5 dB were noticed for different values when $\Delta f < RBW$.

4) Calculation of total average electric field (Fig. 2)

The total average electric field is obtained by multiplying the maximum hold value E_{tot}^{active} (= average active electric field) with the appropriate duty cycle:

$$E_{tot}^{avg} = E_{tot}^{active} \cdot \sqrt{T} \ \ [\mathrm{Vm}^{-1}] \tag{5}$$

The value of E_{tot}^{avg} can then be compared with the guidelines of e.g., ICNIRP 1998 to check compliance. The total duration for the execution of the WLAN exposure measurements is then the following:

$$duration = N \cdot 77 + 180 \, [\mathrm{s}] \tag{6}$$

N is the number of WLAN channels, 77 seconds is the duration needed to measure 2,200 single sweeps to determine T with the settings of Table 2, and 180 s or 3 minutes is three times the duration for 1 electric-field component for the max-hold setting until the signal stabilizes (1 minute). Thus if 13 WLAN channels (maximum number of WLAN channels in Belgium) have to be measured the total measurement time for accurate estimation of WLAN exposure on a location is 19.7 minutes. This is much less than measuring 13 channels times 6 minutes times 3 components (234 minutes, ICNIRP 1998) or 13 channels times 30 minutes times 3 components (1170 minutes, IEEE C95.1 2005, FCC 2001).

We do not perform zero-span (time-domain) measurements for the assessment of the field due to the much longer duration required to perform accurate measurements: for max-hold measurements in the frequency domain, all channels in the 2.4 GHz band are measured in one trace during a period of 1 minute. Using the zero-span mode, for *each orthogonal component* each separate channel has to be measured during 1 minute until the signal stabilizes. This results in a measurement time, which is 13 times larger if 13 Wi-Fi channels are present. Moreover, the RBW of SAs is mostly much lower than the bandwidth of the WLAN signals. Using the proposed method, WLAN exposure is assessed at 222 locations.

C. Validation of method and comparison with 6 and 30 minutes time averaging

In this section the procedure of Section II is validated by performing measurements of the D-Link and WiLab AP, during different time durations up to 6 minutes (ICNIRP) and 30 minutes (IEEE C95.1). The APs and measurement probe are located in the office environment. At a distance of 50 cm from the APs, the electric field is measured with the RMS detector, an RBW = 1 MHz, span of 100 MHz and different SWTs (Table 2). We define the deviation Δ of average field value E_{tot}^{avg} with respect to the correct value $E_{tot,corr}^{avg}$ as follows:

$$Deviation\,\Delta = 20 \cdot \log\left(\frac{E_{tot}^{avg}}{E_{tot,corr}^{avg}}\right) \quad [\mathrm{dB}] \tag{7}$$

If $\Delta < 0$ then an underestimation occurs with respect to the correct value, if $\Delta > 0$ then an overestimation occurs. The results of the validation measurements for the D-Link and WiLab AP are shown in Table 3. $E_{tot,corr}^{avg}$ is determined by using a SWT = 100 ms for the WiLab AP and of 260 ms for the D-Link AP. The results are also compared with the method of Foster 2007, where a SWT of 0.9 s is used and the average value over 64 sweeps is determined.

For the WiLab AP in broadcast mode at a distance of 50 cm, $E_{tot,corr}^{avg} = 6.3$ V/m (9.7 times below the 61 V/m ICNIRP 1998 guideline) (SWT = 100 ms). For the D-Link AP at 50 cm $E_{tot,corr}^{avg}$ = 0.21 V/m (290.4 times below the 61 V/m ICNIRP 1998 guideline). If the inter pixel time *IPT* is larger than t_{active} (SWT > SWT_{corr}), the signal is underestimated (maximal deviations Δ of -1.8 and -23.2 dB for WiLab and D-Link AP, respectively). If *IPT* is smaller (SWT < SWT_{corr}), an overestimation (worst-case approach, $\Delta > 0$) is obtained. The setting of the SWT is thus very important.

In Table 3, large deviations up to 23.2 dB when applying the proposed method are obtained for the D-Link AP for SWT $\geq$ 1 s (small duty cycle *T* of 0.6 %) because the *IPT* is much smaller than the period of the signal (beacon of 100 ms in contrast to the broadcast mode of the WiLab AP) and at the same time t_{active} (Table 1) is lower than *IPT*. Therefore the RMS value per pixel is not measured for the entire active period but only for a random part of the signal.

Table 3 shows also the results for the assessment of the exposure according to ICNIRP 1998 and IEEE C95.1 2005 (very time-intensive): the measured value gives low deviations from 0.2 dB to 1.1 dB from the correct value, for the D-Link and WiLab AP, respectively. This shows that our method with optimal settings of SWT (when the signal is known) and a SWT = 10 ms (when the signal is not known) gives results as accurate as the values obtained in accordance with ICNIRP 1998 and IEEE C95.1 2005.

For the high duty cycles of the WiLab AP (86 %), the method of Foster 2007 is a good approach. Only deviations of 1.01 dB occurred. But for low duty cycles of the D-Link AP (0.6 %), the SWT of 0.9 s is too low to obtain accurate average values, resulting in deviations of 2.54 dB (overestimation, Table 3). Thus for low duty cycles (that often appear in practical circumstances), the approach of Foster 2007 should be changed.

III. RESULTS

A. Field measurements close to one single access point

Fig. 6 shows the electric fields as a function of the distance (30 cm up to 4 m) for the D-Link and WiLab AP (settings of SA in Table 2) in an office environment. The APs are located at 1.5 m above floor level (on a table) and the measurements are executed at the same height. Two orientations of the antennas are considered: horizontal and vertical. For distances smaller than 1 m, the fields due to the vertical orientation are higher (in main beam of WLAN antennas). When the separation is larger than 1 m, then similar values are obtained due to the multipath environment. The fields decrease with distance: for the WiLab AP we obtain about 10.7 V/m at 30 cm and 2.2 V/m at 4 m but the influence of the multipath environment (reflections, diffractions) can clearly be noticed e.g., the increased field strength at 2.5 m. These values due to the WiLab AP (Fig. 6) are high compared to values reported in literature (Myhr 2004, Hamnerius 2005, Foster 2007, Kuhn et al. 2007) and higher than the ones of the D-Link AP. The reason is the high duty cycle of about 86 %, which can be used in the WiLab wireless sensor testbed. For the D-Link AP (duty cycles ranging from 0.5 to 1.4 %), values from 0.15 V/m to 0.37 V/m are obtained.

All values of Fig. 6 satisfy the ICNIRP guidelines for general public exposure (61 V/m in the 2.4 GHz band, ICNIRP 1998). Exposure to the WiLab and D-Link APs are about 5.7 times (10.7 V/m) and 165 times (0.37 V/m) lower than the ICNIRP reference values, respectively.

B. Influence of different nodes at 1 location

In this section we investigate the influence of different APs on the field values at a single position. Therefore, consecutive measurements are executed at a single position at 1.5 m above floor level with 1, 2, …, 6 APs active, respectively. The configuration of the room where the measurements were executed is shown in Fig. 7 (all the APs have an identification number, which is also shown in this figure). The APs are attached to the ceiling at a height of 2.7 m above the floor. The separation between two active APs is 4.9 m. The distance from the measurement location to the closest AP is 2.7 m. Two orientations are again considered: horizontal and vertical orientation of the antennas of the APs. All APs transmit in broadcast mode with a maximal throughput of 54 Mbps at channel 8 (2.447 GHz) with a maximal radiated power of 20 dBm. The duty cycle T of a single WiLab AP is 86 %, when multiple WiLab APs are radiating the duty cycle for exposure assessment increases to 91 % because the WiLab APs communicate independently (CSMA/CA protocol is ignored, see Section II.A).

Fig. 8 shows that the maximal value of E_{tot}^{avg} for horizontal orientation was measured with all 6 APs active and this value is equal to 2.93 V/m (20.8 times lower than the 61 V/m ICNIRP 1998 guideline). For the vertical configuration a maximal value of E_{tot}^{avg} equal to 2.86 V/m is measured when 5 APs are active. We can conclude from Fig. 8 that increasing the number of APs increases slightly the electric field values: fields of about 1 V/m for a single AP up to 2.9 V/m for 6 APs are obtained for both orientations. Both orientations give similar field values as already mentioned above (for distances to AP > 1 m). Through sweeping the area with the broadband probe (PMM-EP330: Narda Safety Test Solutions,Via Leonardo da Vinci, 21/23—20090 Segrate, Milano, Italy; http://www.pmm.it), the location of the maximal field value in the room is identified for 6 active APs (indicated in Fig. 7). This maximal value is equal to 4.4 V/m for the horizontal orientation and 5.9 V/m for the vertical orientation.

C. Field measurements at different locations

In total 222 measurement positions are considered, where exposure is measured for all present WLAN signals: 27 with WiLab off, 195 with WiLab on.

Twelve relevant positions spread over the three floors of the office building are discussed here in a more detailed way. These positions are selected where high WLAN exposure is possible, e.g., in the neighborhood of APs where the general public has access. WLAN exposure is determined for 7 WLANs. The WiLab network is for the first measurement batch switched off and then switched on to compare the WLAN exposure.

1) WiLab OFF

Measurements are performed from 80 MHz up to 3 GHz at the selected positions. Fig. 9 shows the wireless signals present on the first floor of the office building: an FM signal, GSM900 (900 MHz), GSM1800 (1800 MHz), DECT (Digital Enhanced Cordless Telecommunications) and Wi-Fi signals are present. WLAN channels are detected (with Airmagnet) and measured at channels 1, 3, 4, 6, 7, 11, 13. Duty cycles of 0.4 % to 2.8 % and once 9.7 % are obtained. Average exposure to WLAN (WiLab off) is 0.12 V/m and a 95th percentile of 0.90 V/m is obtained (68 times below the ICNIRP 1998 guidelines). The standard deviation is 0.60 V/m. These values are comparable with those of Myhr 2004 (maximum average power density of 1.72 mW/m^2 or 0.81 V/m) and those of Foster 2007 (maximum 7 mW/m^2 or 1.62 V/m for WLAN APs). Kuhn et al. 2007 reported worst-case electric-field values of 0.3 to 1.1 V/m at 1 m from 802.11 APs. Schmid 2007 also reported values lower than 2.7 V/m (or 20 mW/m^2).

Fig. 10 summarizes the exposure values at the 12 different positions (discussion in next section, the error bars are calculated from the uncertainties of the experimental values). The highest values (WiLab off) are measured at positions 5 (0.26 V/m), 6 (0.50 V/m), and 10 (0.49 V/m), which are located close to different APs.

2) All locations and all measurements with WiLab on

In total 195 positions are selected to perform WLAN measurements to characterize exposure to the WiLab. When the WiLab is on, all WiLab APs transmit maximal in broadcast mode: average exposure increases to 1.9 V/m, and the 95^{th} percentile is 4.7 V/m (13 times below the ICNIRP guidelines). The standard deviation is 1.41 V/m. The maximal measured field value is 6.7 V/m when only distances of more than 1 m from APs are considered (9.1 times below ICNIRP guidelines).

Fig. 10 compares the WLAN exposure with and without WiLab. The error bars in Fig. 10 are calculated from the uncertainties of the experimental values. The increase due to the WiLab is clearly visible. The two higher field values for the 12 positions are 6.7 V/m (position 11) and 6.1 V/m (position 4).

All values are thus below the ICNIRP guidelines of 61 V/m but are higher than those reported by Myhr 2004 and Foster 2007. The exposure due to the “normal” APs (low duty cycles of typical 0.5 to 2.8 %) is much lower than the exposure to the WiLab (duty cycles of 86 to 100 %) due to the much lower duty cycles. By stimulating all WiLab nodes at maximal power, the highest fields increase by a factor 13.4 for the 12 positions (6.7 V/m versus 0.50 V/m).

IV. CONCLUSIONS

A correct measurement procedure to determine WLAN radiofrequency exposure of the general public and to evaluate compliance with international safety guidelines is proposed. This is the first paper where all optimal settings of the measurement equipment (i.e., spectrum analyzer) used for the WLAN exposure assessment are discussed and recommended, enabling other researchers to perform correct measurements. It is shown that these settings have a huge influence on the measurement results and that it is very important to specify these.

A new fast procedure to perform measurements during about 1 minute per orthogonal field component and obtain results that are representative for 6 and 30 minutes exposure (specified in ICNIRP 1998 and IEEE C95.1 2005 guidelines) is presented. We recommend to use the settings presented in Table 2. Typical duty cycles of about 0.5 % are obtained for "normal" APs, while duty cycles of 86 % are possible in the WiLab (wireless sensor testbed).

Finally, WLAN exposure is measured on-site and determined for 7 Wi-Fi networks in an office environment at 222 locations and for the first time general public exposure in a wireless sensor testbed (200 WiLab nodes with each 2 Wi-Fi IEEE 802.11 radios) is determined. Average WLAN exposures of 0.12 V/m and 1.9 V/m, and 95th percentiles of 0.90 V/m and 4.7 V/m are obtained with and without WiLab, respectively. WLAN exposures are at least 9.1 times below the ICNIRP guidelines for distances of more than 1 m from the APs**.** All values satisfy thus the international guidelines but exposure due to the wireless testbed is significantly higher due to the much higher duty cycles.

Future research may consist of performing large measurement campaigns using the proposed measurement procedure in order to obtain a statistically accurate WLAN exposure distribution in office environments.

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Table 2: Summary of the recommended settings of the spectrum analyzer for the assessment of WLAN exposure.

Table 3: Results of validation measurements at 50 cm from D-Link and WiLab AP with optimal settings and different SWT.

Figure 1: Single sweep of WLAN signal of WiLab (broadcast mode) and D-Link (idle mode) AP with SA in zero span mode (RBW = 20 MHz, RMS detector, SWT = 2.5 ms).

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Figure 6: Electric field of WiLab and D-Link AP as a function of distance for two antenna orientations (office environment).

Figure 7: Configuration of APs in room and location of measurement position.

Figure 8: Electric field E_{tot}^{avg} *[V/m] at a location versus the number of WiLab APs for two antenna orientations.*

Figure 9: Electric field as a function of the frequency (range of 80 MHz up to 3 GHz) on the first floor of the office building.

Figure 10: Electric field E_{tot}^{avg} *[V/m] for WiLab off (white bars) and WiLab on (gray bars).*

Table

access point	datarate [Mbps]	length physical frame [s]	t_{active} [μs]	optimal SWT [ms]
D-Link (idle mode)	2	$192 \cdot 10^{-6} + \frac{90 \cdot 8}{2 \cdot 10^6} + \frac{4 \cdot 8}{2 \cdot 10^6}$	568	258.4
WiLab (broadcast mode)	54	$20 \cdot 10^{-6} + \frac{1264 \cdot 8}{54 \cdot 10^6} + \frac{4 \cdot 8}{54 \cdot 10^6}$	209	95.1

Table 1

Table

measurement method	parameter	value
duty cycle single sweep zero span mode	center frequency [MHz]	channel frequency 2412 + k·5 with k = 0, 1, …, 12
	RBW [MHz]	1
	SWT [ms]	1
	VBW [MHz]	10
	detector	RMS detector
	span [MHz]	0
	number of single sweeps	2200
max-hold measurement in frequency domain	center frequency [GHz]	2.45
	RBW [MHz]	1
	SWT [ms]	10 if signal is not known t_{active}×n if signal is known
	VBW [MHz]	10
	detector	RMS-detector
	span [MHz]	100
	maximum hold time	1 minute or until signal stabilizes

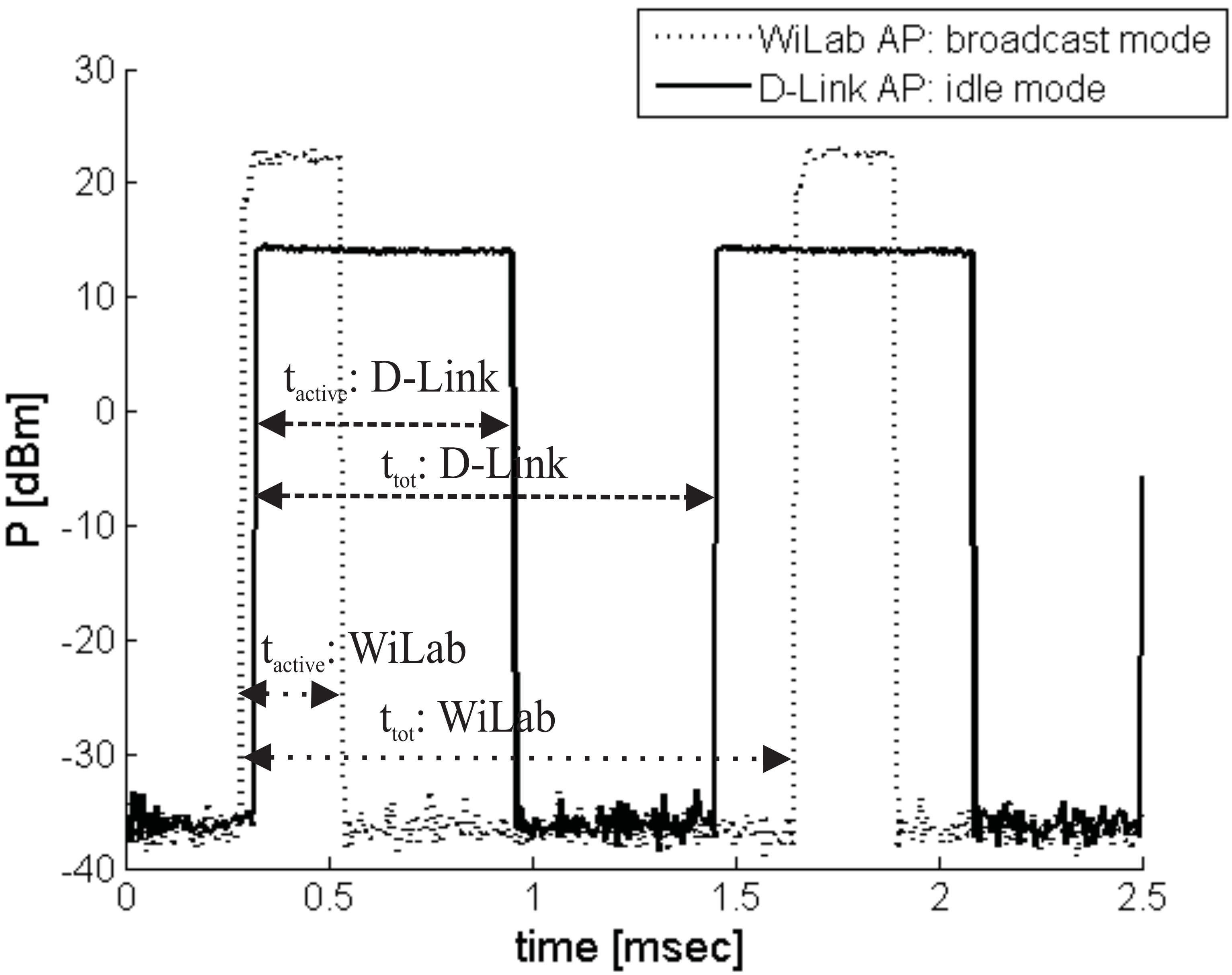
Table 2

Table

own method	SWT	max-hold time	WiLab AP $E_{tot,corr}^{avg}$ = 6.32 V/m		D-Link AP $E_{tot,corr}^{avg}$ = 0.21 V/m	
			E_{tot}^{avg} [V/m]	Δ [dB]	E_{tot}^{avg} [V/m]	Δ [dB]
	2.5 ms	60 s	7.00	0.89	0.23	0.91
	10 ms	60 s	6.62	0.40	0.22	0.60
	WiLab: 100 ms	60 s	**6.32**	**0.00**	**-**	**-**
	D-Link: 260 ms		-	-	**0.21**	**0.00**
	1 sec	60 s	5.74	-0.83	0.12	-5.11
	60 sec	60 s	5.35	-1.44	0.02	-22.20
	6 min	6 min	5.74	-1.75	0.01	-23.17
	30 min	30 min	5.77	-1.44	0.01	-23.17
	SWT	max-hold time	E_{tot}^{active} [V/m]	Δ [dB]	E_{tot}^{active} [V/m]	Δ [dB]
ICNIRP	6 min	6 min	5.57	-1.09	0.21	-0.17
IEEE C95.1-2005	30 min	30 min	5.77	-0.79	0.21	-0.17
Foster	0.9 sec	Single sweep (RMS)	5.62	-1.01	0.28	2.54

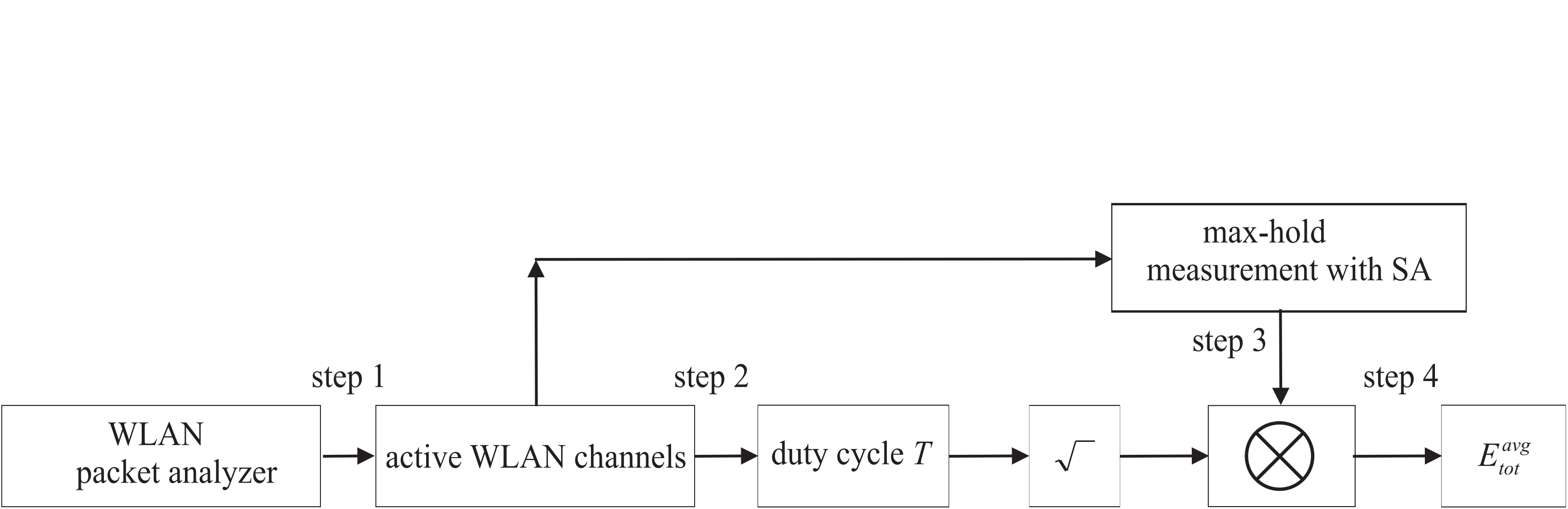
Table 3

Figure

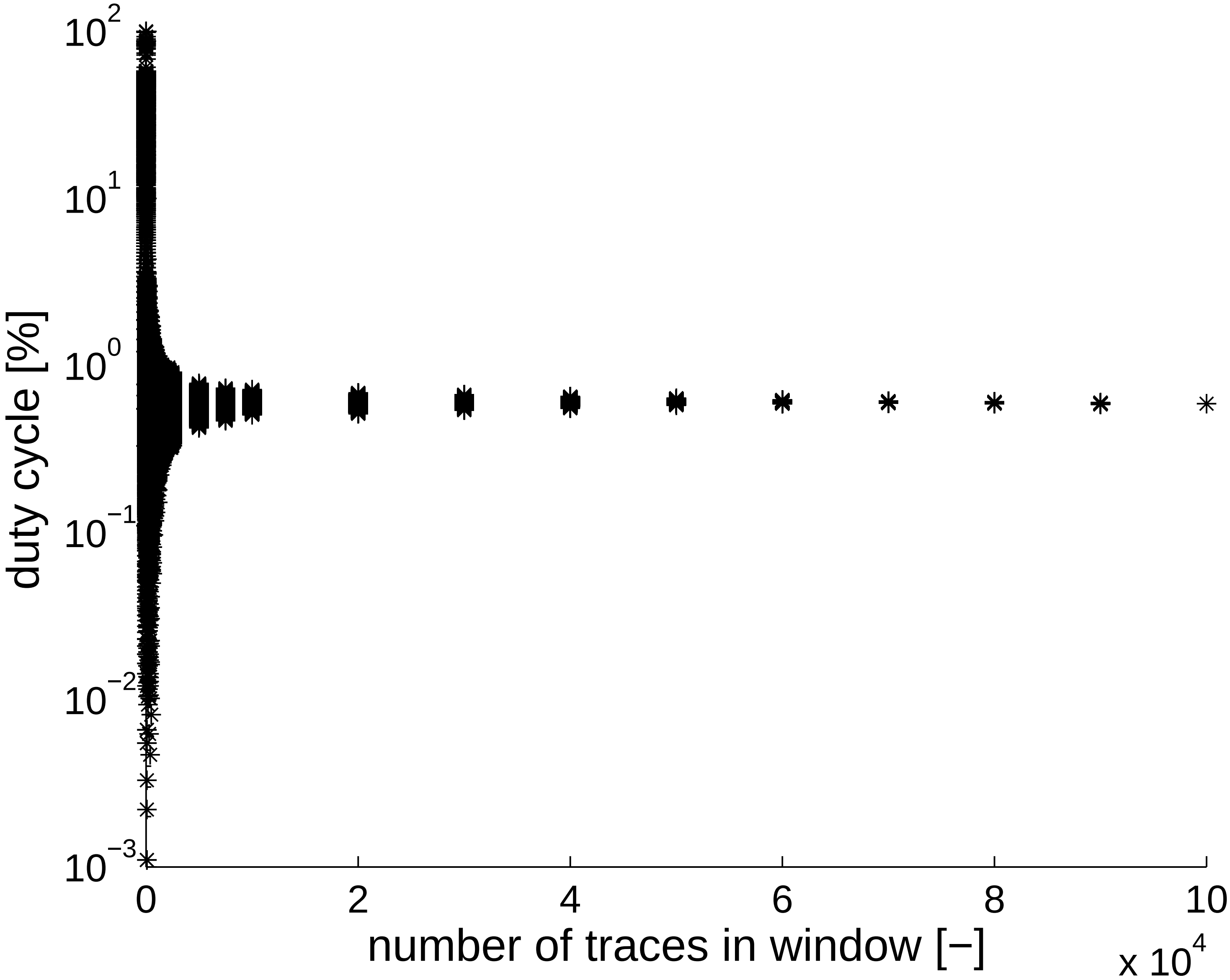


WiLab AP: broadcast mode
D-Link AP: idle mode
30
20
10
0
-10
-20
-30
-40
P [dBm]
t_{active}: D-Link
t_{tot}: D-Link
t_{active}: WiLab
t_{tot}: WiLab
0
0.5
1
1.5
2
2.5
time [msec]

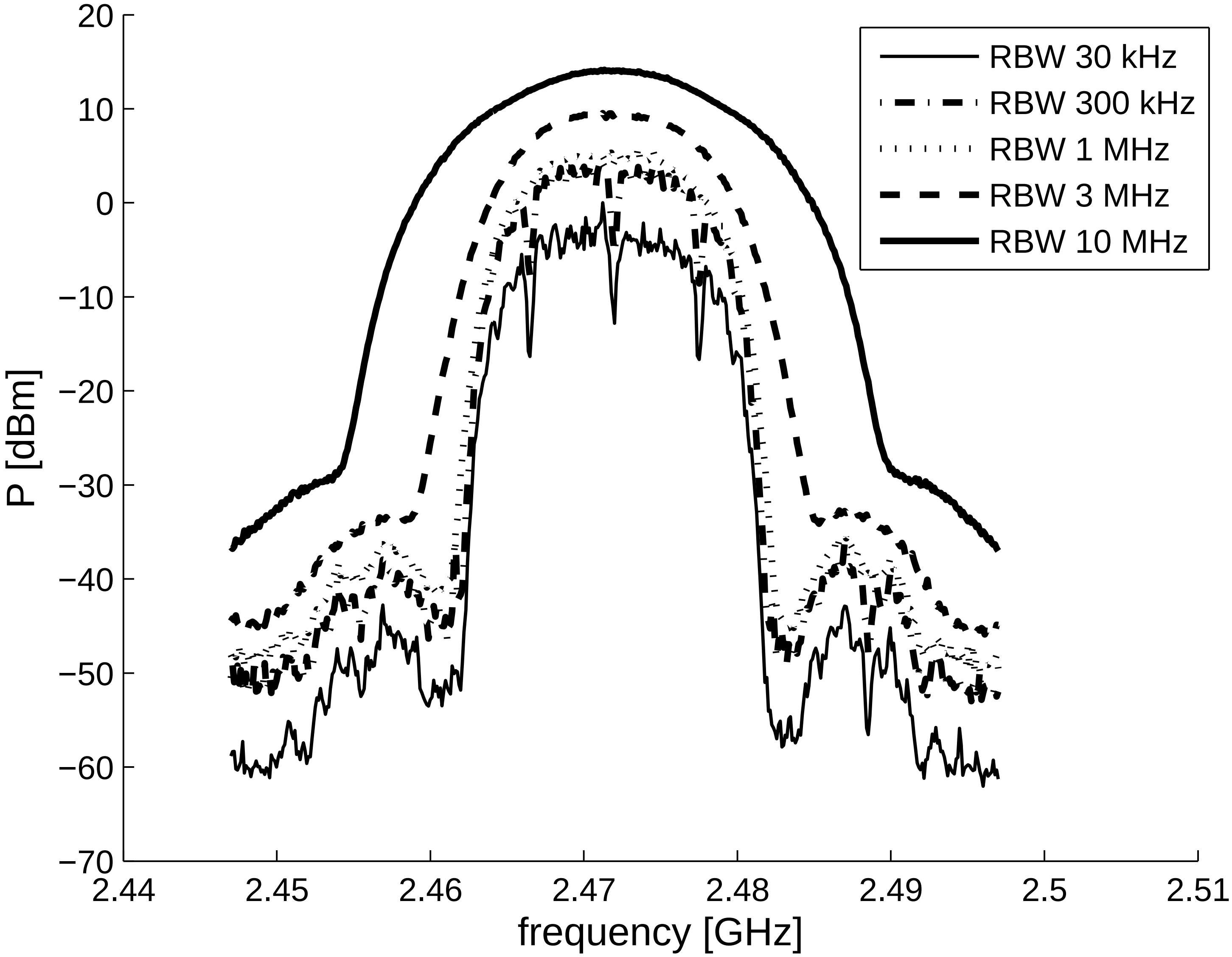
Figure


max-hold
measurement with SA
step 1
step 2
step 3
step 4
WLAN
packet analyzer
active WLAN channels
duty cycle T
$\sqrt{\ }$
E_{tot}^{avg}

Figure

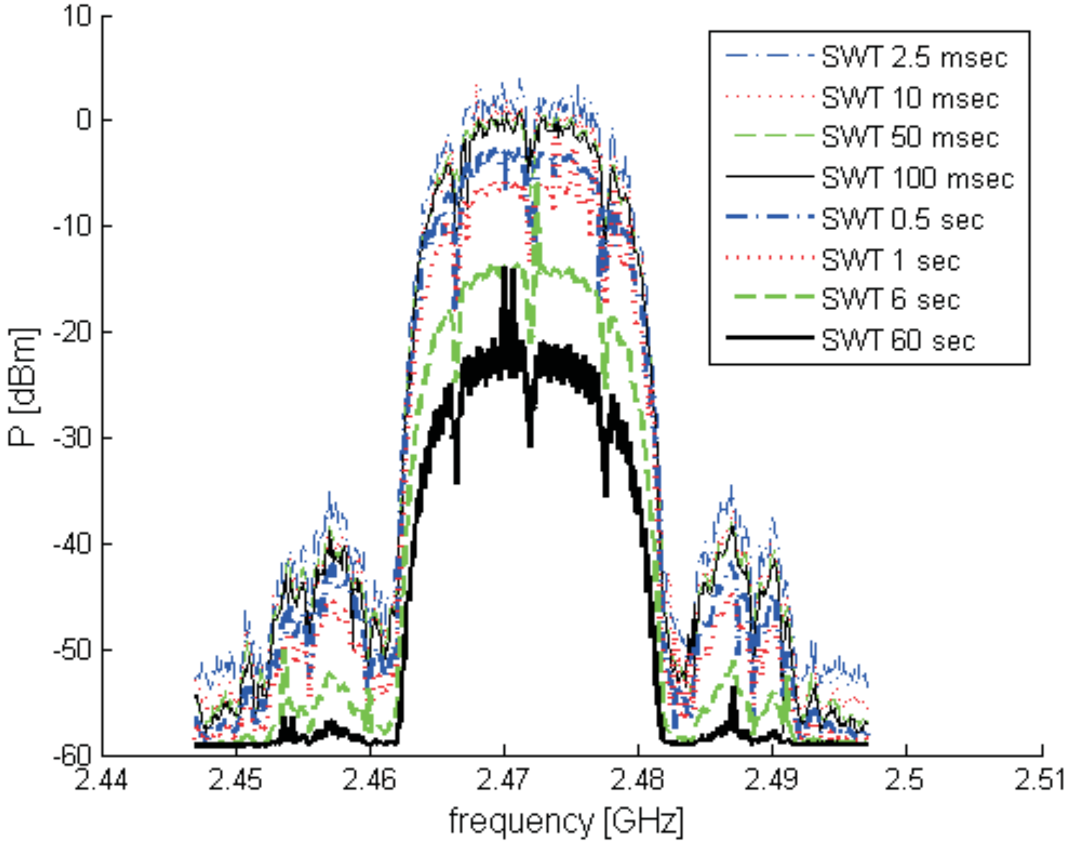

duty cycle [%]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
10
number of traces in window [−]
x 10^4

Figure

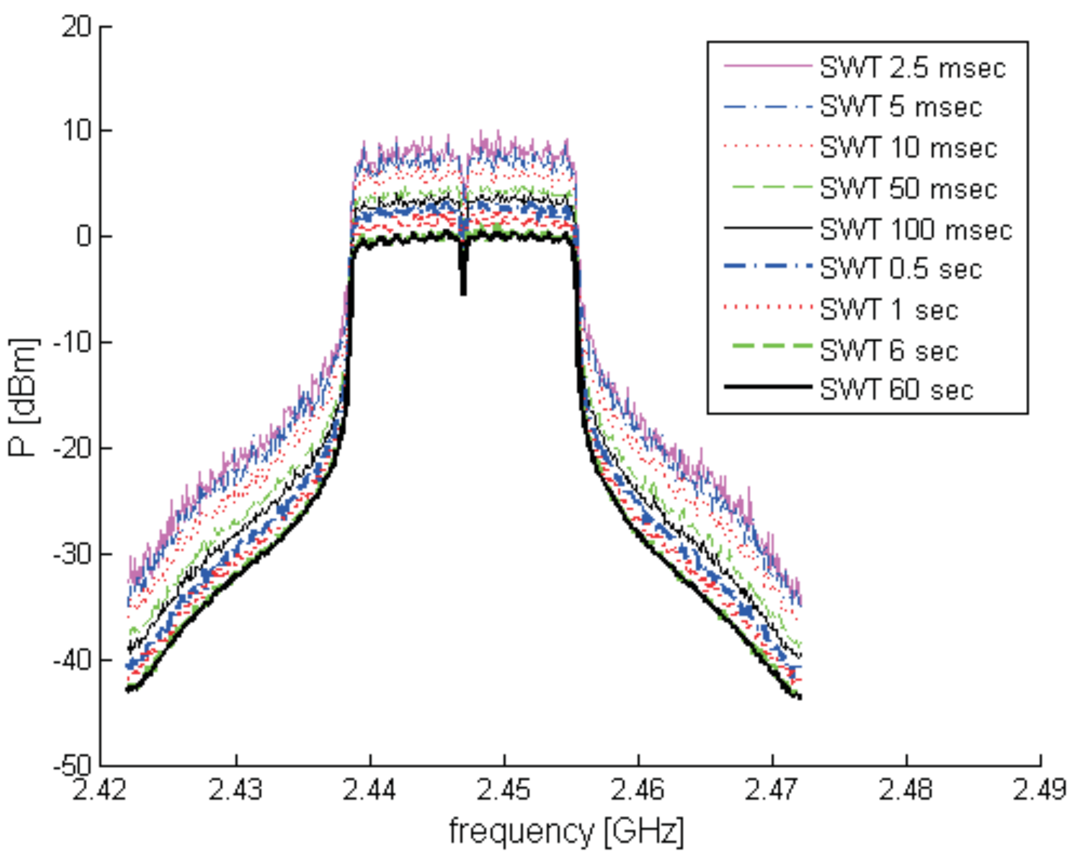


RBW 30 kHz
RBW 300 kHz
RBW 1 MHz
RBW 3 MHz
RBW 10 MHz
P [dBm]
frequency [GHz]
20
10
0
−10
−20
−30
−40
−50
−60
−70
2.44
2.45
2.46
2.47
2.48
2.49
2.5
2.51

Figure

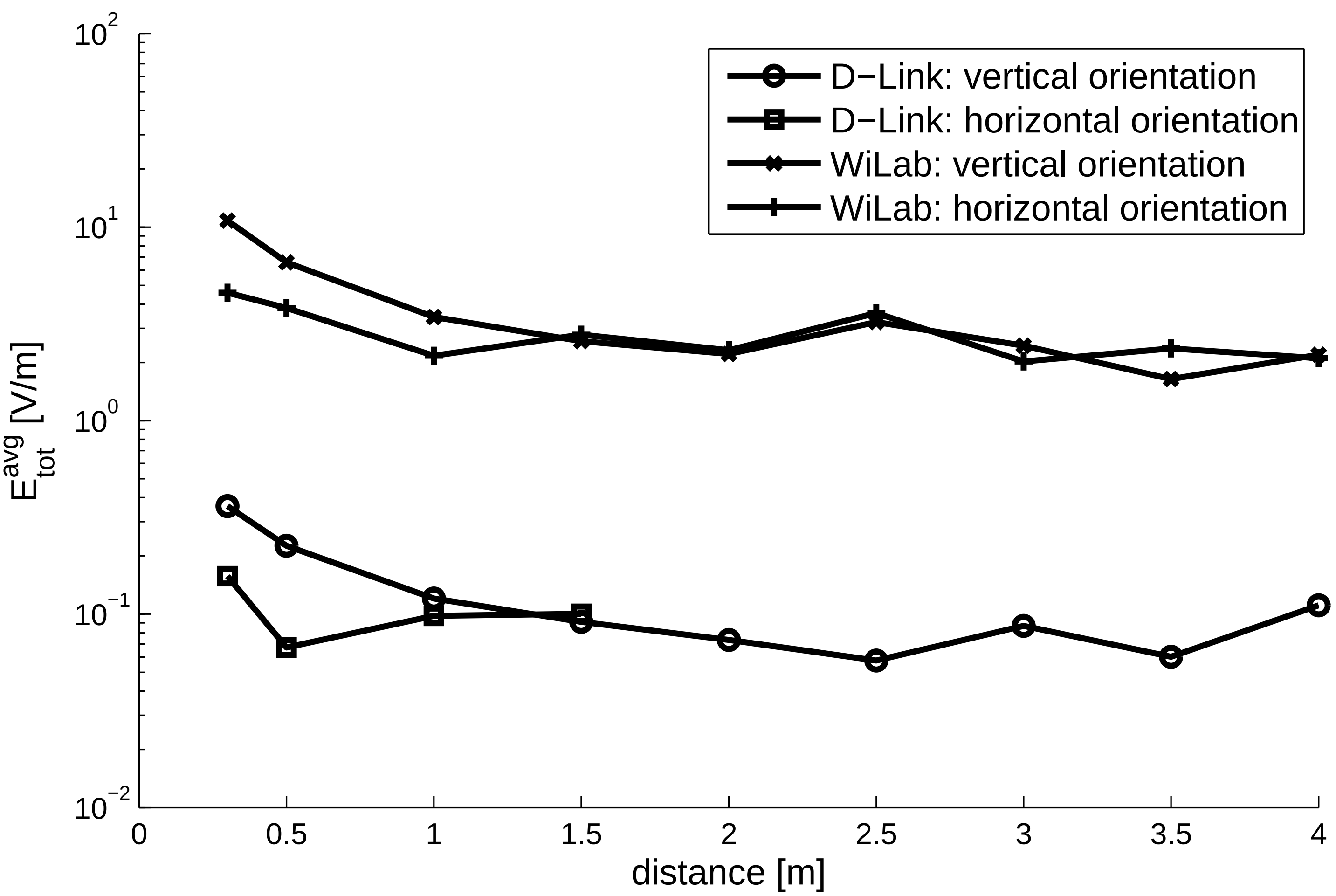

SWT 2.5 msec
SWT 10 msec
SWT 50 msec
SWT 100 msec
SWT 0.5 sec
SWT 1 sec
SWT 6 sec
SWT 60 sec
P [dBm]
frequency [GHz]
10
0
-10
-20
-30
-40
-50
-60
2.44
2.45
2.46
2.47
2.48
2.49
2.5
2.51

(a)


SWT 2.5 msec
SWT 5 msec
SWT 10 msec
SWT 50 msec
SWT 100 msec
SWT 0.5 sec
SWT 1 sec
SWT 6 sec
SWT 60 sec
P [dBm]
frequency [GHz]
20
10
0
-10
-20
-30
-40
-50
2.42
2.43
2.44
2.45
2.46
2.47
2.48
2.49

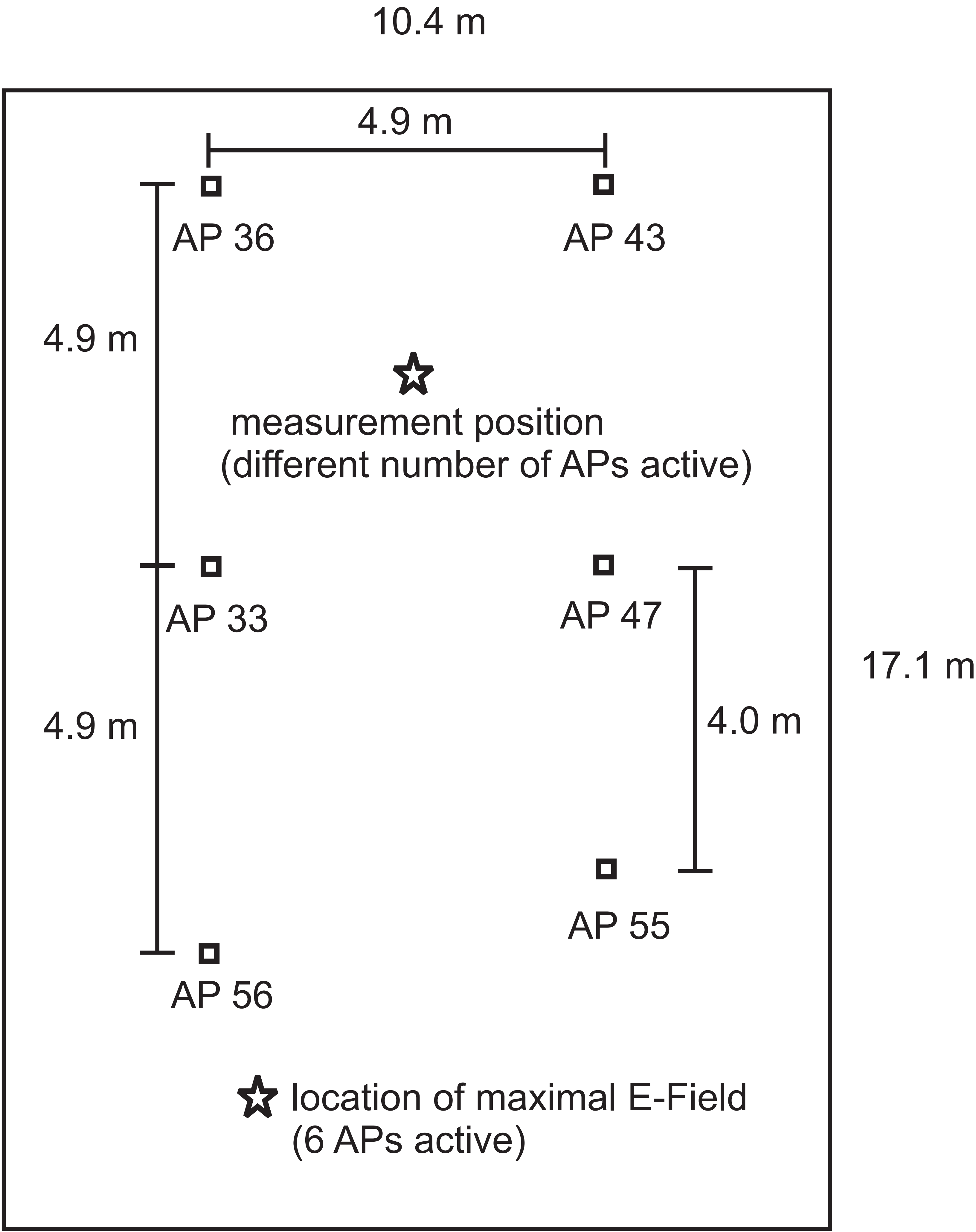
(b)

Figure



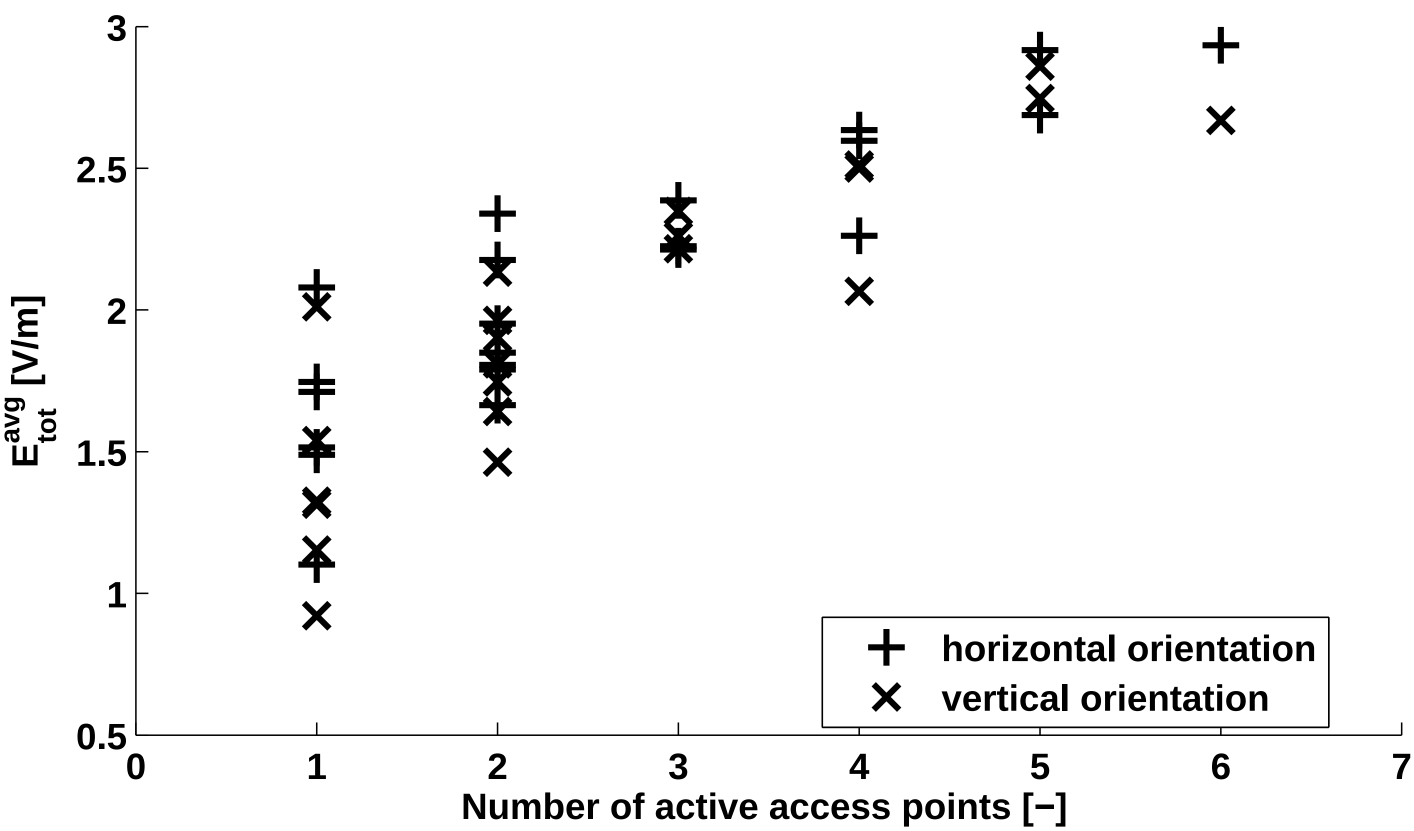
D−Link: vertical orientation
D−Link: horizontal orientation
WiLab: vertical orientation
WiLab: horizontal orientation
E_{tot}^{avg} [V/m]
distance [m]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
0.5
1
1.5
2
2.5
3
3.5
4

Figure

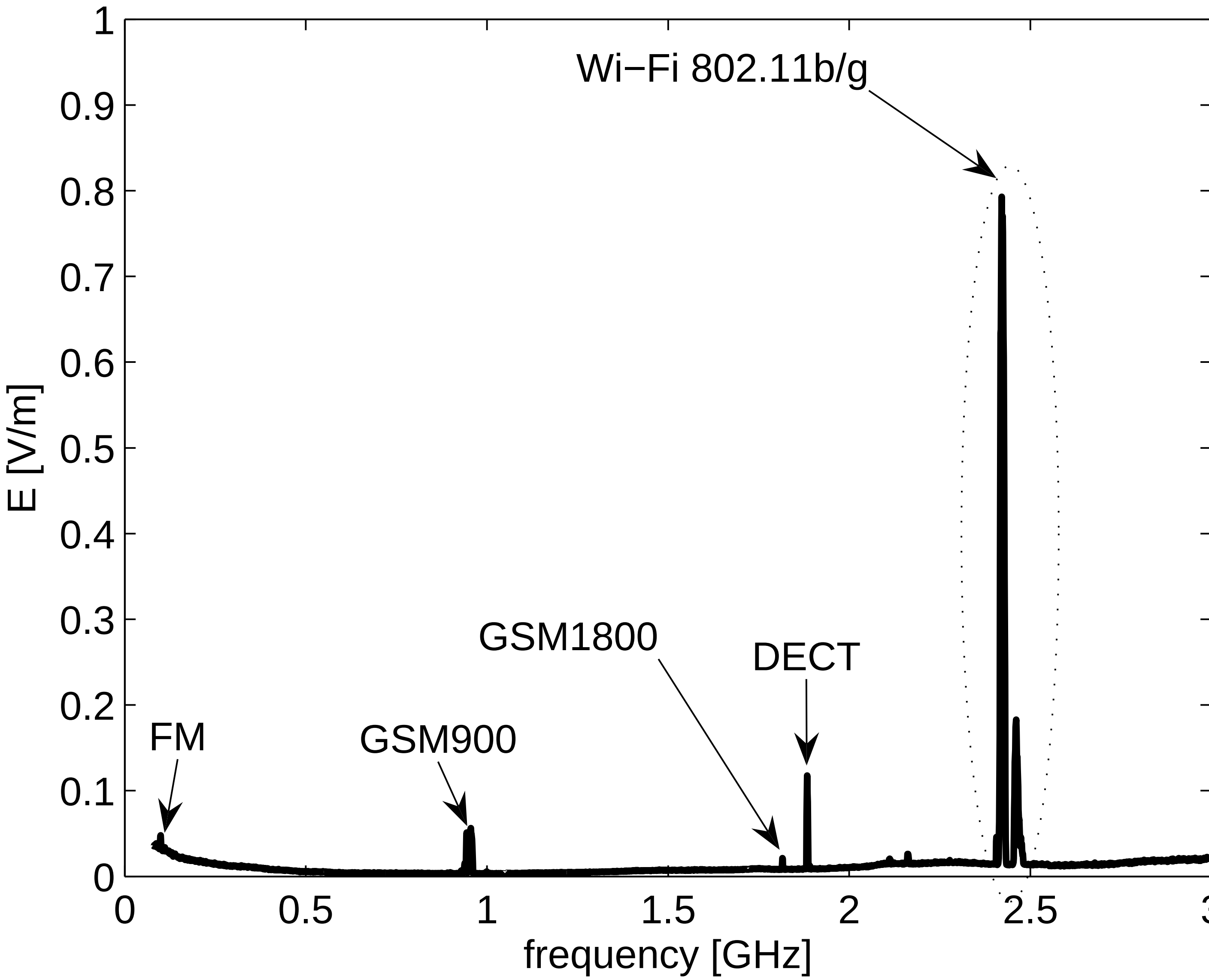


10.4 m
4.9 m
AP 36
AP 43
4.9 m
measurement position
(different number of APs active)
AP 33
AP 47
17.1 m
4.0 m
4.9 m
AP 55
AP 56
location of maximal E-Field
(6 APs active)

Figure

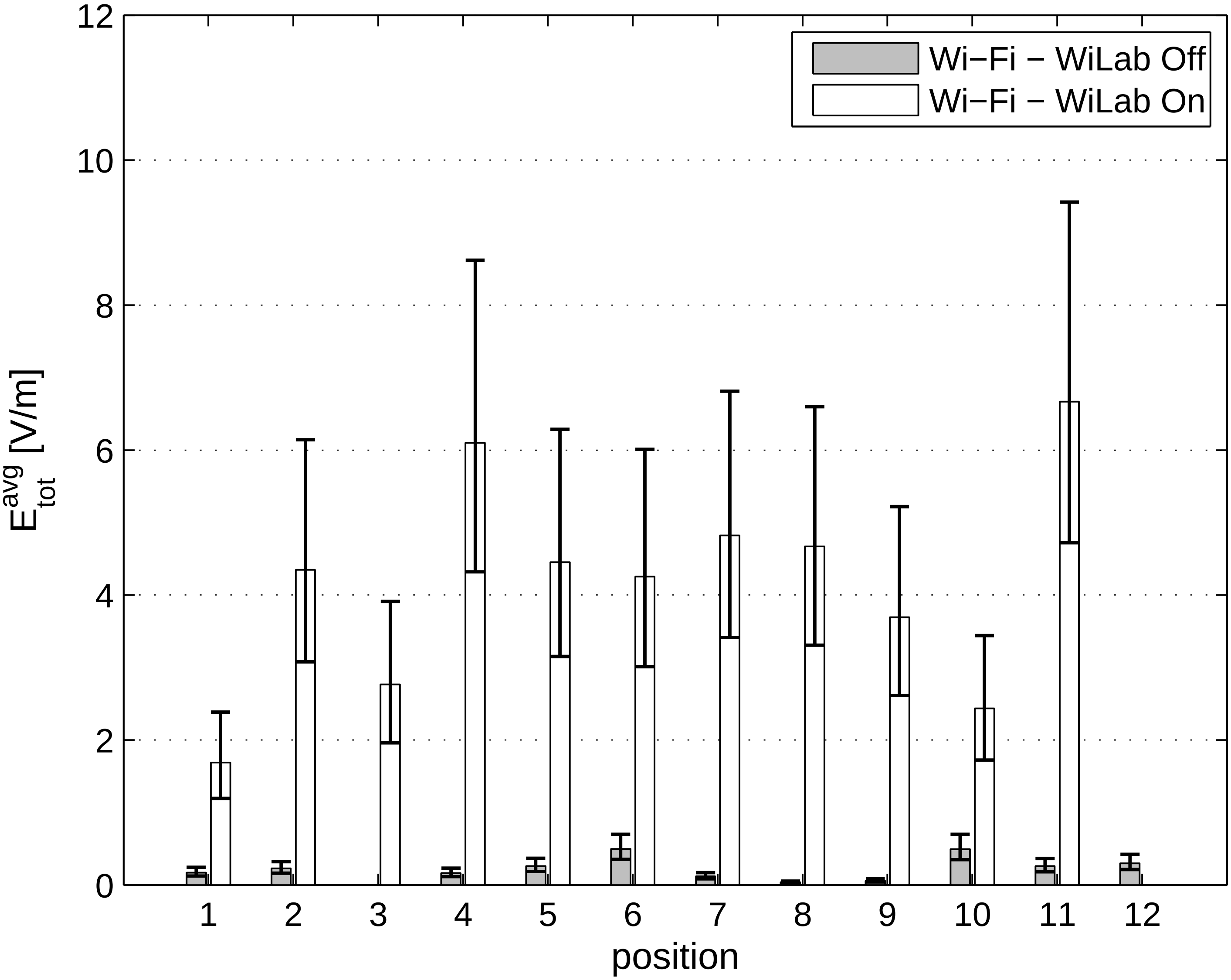

3
2.5
2
1.5
1
0.5
0
1
2
3
4
5
6
7
E_{tot}^{avg} [V/m]
Number of active access points [−]
horizontal orientation
vertical orientation

Figure



Wi−Fi 802.11b/g
GSM1800
DECT
FM
GSM900
E [V/m]
frequency [GHz]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5
3

Figure



Wi−Fi − WiLab Off
Wi−Fi − WiLab On
E_{tot}^{avg} [V/m]
position
0
2
4
6
8
10
12
1
2
3
4
5
6
7
8
9
10
11
12