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Comparison of 2.4 and 5 GHz WLAN Network for Purpose of Indoor and Outdoor Location

Łukasz Chruszczyk, Adam Zając and Damian Grzechca

***Abstract*—This paper presents comparison of prototype location system built with standard components of 2.4 and 5 GHz WLAN network infrastructure. The system can be used for personal or other objects' positioning, both for indoor and outdoor environments. The system is local, i.e. its operational area is limited to WLAN network operating range. The system is based on standard and widely available WLAN components (access points, network adapters). The goal is to avoid any hardware and software modifications. Also position calculation should not be power hungry operation. Method of location is based in Received Signal Strength Indication (RSSI) returned by most of RF ICs (including WLAN). The main focus is research of how much accuracy (and usefulness) can be expected from standard WLAN hardware. Both static and dynamic scenarios have been tested and compared.**

***Keywords*—indoor location, personal location, wireless LAN, RSSI measurement**

I. INTRODUCTION

NAVIGATION is one of the most important technical issue of all times – starting with first lighthouse in 400 BC, towards improving maritime navigation systems in Middle Ages, through long range systems (e.g. Omega, Loran), ending with true global navigation: satellite GPS in the 1970s. The last mentioned system is constantly developing and it is used by many different applications, working in different environments.

The most popular and used global satellite navigation systems are GPS and Glonass (with Galileo and Beidou in future). These systems have enough accuracy for most applications in their free/civilian versions. Constant progress in electronics made them affordable and truly portable: small, light and less power-hungry devices. Unfortunately, this progress is not enough yet to overcome main limitations of currently available receivers: noise figure. Thus, all nowadays satellite navigation can be used only in outdoor environment. On the other hand, there are still missing effective alternatives for indoor use. Although there has been proposed a variety of location methods, based on various physical phenomena (e.g. video, ultrasound, MEMS dynamics, UWB pulses), none of them became dominating [1-9]. The main reasons are:

- high cost of infrastructure,
- high cost or power consumption of data processing,
- unacceptably low accuracy.

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The infrastructure used in proposed prototype indoor systems is based on existing WLAN infrastructure. There are many ways of gathering data from WLAN access points (AP). Mentioned approaches are based on analysis of the following signal parameters [10]:

- Time of Arrival (TOA),
- Time Difference of Arrival (TDOA),
- Angle of Arrival (AOA),
- Received Signal Strength Indication (RSSI).

Data gathered using one these methods can be applied in selected algorithms to:

- compute distance between user and network APs of known coordinates,
- compare gathered data with previously prepared map of signal parameters for the location, where system is running (fingerprinting).

System which is a subject of this paper uses RSSI values to compute distances between user and corresponding WLAN APs points. It must be noted that RSSI is not a Received Signal Power Indication (RSPI) – a true received signal power measurement. Such systems are much more expensive and impractical in scope of consumer electronics.

The used RSSI is assumed to be time-invariable function of a RSPI, defined (with some accuracy) by manufacturer of a WLAN RF IC. It is further altered by receiving path (antenna, PCB transmission line, impedance mismatch etc.). However, it is assumed that the total relation between RSSI and a received signal is similar and constant for all used devices.

Main difficulties, that have influence on system accuracy are:

- reflection, diffraction and dissipation of electromagnetic waves in a building environment,
- existence of interfering signals.

One of main objectives of this paper is to compare the system accuracy in two available 802.11 frequency bands: 2.4 GHz and 5 GHz. Comparison is based on system tests in two environments: indoor and outdoor.

The tests included both static (motionless user) and dynamic scenarios (user in motion). In both cases, APs of known position (infrastructure) are devices that broadcast their service set identifiers (SSID) - beacon frames. User position is calculated using RSSI of received signals and with known APs positions (fig. 1). Such approach have following advantages:

- concurrent operation of WLAN network and location system,
- software or hardware modification of the infrastructure (AP) is not needed,
- no hardware modification of user device is necessary – most currently used RF ICs provide RSSI read-out,
- position calculation requires very little computational power (see further details).

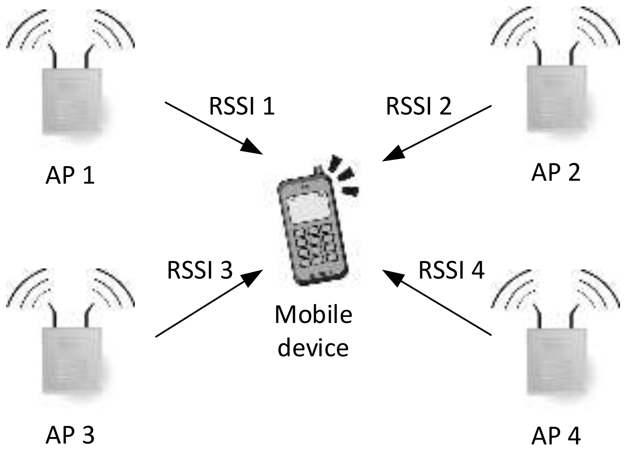

Fig. 1. Location system schema.

There are possible two scenarios of user operation. In both cases the mobile device must measure RSSI values of at least 3 APs. In first scenario, based on known APs' positions (e.g. delivered by WWW service) user is able to calculate its own position by itself. In second scenario, user only reads RSSI values of "visible" APs and sends them to remote service, where position is calculated and returned. The latter approach hides APs' positions from user.

II. Mathematical Model

First problem concerned the way of modeling electromagnetic wave dissipation with the distance. In an ideal situation, assuming the wave is propagating in free space, *Friis* equation can be used to compute received power [11, 12]. However for practical reasons, other approach is used, as suggested in [13].

$$RSSI\ [dBm] = RSSI(d_0) - 10n_p log_{10}\left(\frac{d}{d_0}\right) \qquad (1)$$

where:

- d_0 – reference distance of 1 m,
- $RSSI(d_0)$ – RSSI indication at reference distance [dBm],
- n_p – attenuation factor.

The log model has been used for 2.4 GHz frequency band. Other models can be found in [10, 14-16]. After experiments with the system, other equation has been proposed for the 5 GHz frequency band:

$$RSSI\ [dBm] = RSSI(d_0) - 10n_p log_{10}\left(\frac{d}{d_0}\right) - \delta^2 \qquad (2)$$

where:

- δ^2 – variances of previously gathered RSSI in 5 GHz band,
- and the other symbols have the same meaning as in (1).

This original modification, based on [13], improved location accuracy [14-17]. It appears that the motionless user can achieve the biggest advantage. It can be used in order to compute starting position in a well-developed system, i.e. system using fingerprinting. Unfortunately, this approach has not been useful for 2.4 GHz frequency band, because of very high dynamics of the read RSSI values (thus RSSI readout saturation). One of the reasons could be interfering signals in commonly used 2.4 GHz band.

Another way to improve accuracy has been increasing the attenuation factor n_p, if the computed distance has been too long regarding to known geometry of the room. This method has been used for both bands.

After computing the distance d between the receiver and all N access points, with known coordinates x_i and y_i, the next step is to compute the position of the receiver using simple 2D trilateration (fig. 2).

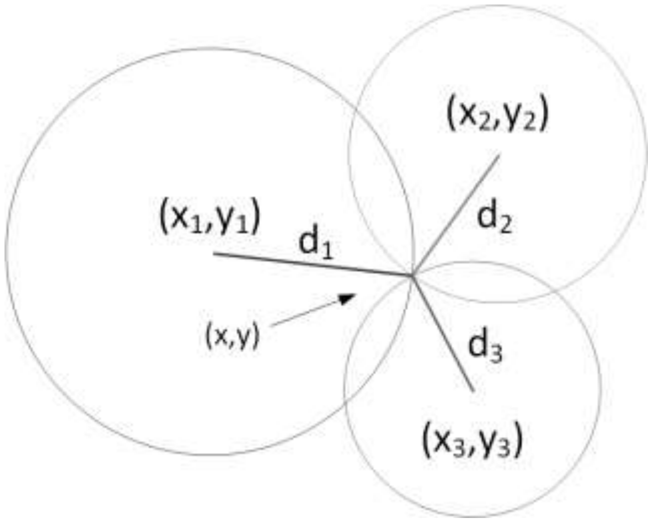

Fig. 2. 2D trilateration example for 3 APs.

Starting point is set of basic circle equations for N access points (3):

$$\begin{cases} d_1^2 = (x - x_1)^2 + (y - y_1)^2 \\ d_2^2 = (x - x_2)^2 + (y - y_2)^2 \\ \vdots \\ d_i^2 = (x - x_i)^2 + (y - y_i)^2 \\ \vdots \\ d_N^2 = (x - x_N)^2 + (y - y_N)^2 \end{cases} \qquad (3)$$
$$i = 1,2 \dots, N - 1$$

where:

- x,y – unknown user position,
- x_i,y_i – known position of i-th AP,
- d_i – distance between user and i-th AP,
- N – total number of APs.

Each formula (i = 1, 2, …, N-1) can be re-arranged as:

$$\begin{cases} x^2 + y^2 = d_1^2 + 2xx_1 + 2yy_1 - x_1^2 - y_1^2 \\ x^2 + y^2 = d_2^2 + 2xx_2 + 2yy_2 - x_2^2 - y_2^2 \\ \vdots \\ x^2 + y^2 = d_i^2 + 2xx_i + 2yy_i - x_i^2 - y_i^2 \\ \vdots \\ x^2 + y^2 = d_N^2 + 2xx_N + 2yy_N - x_N^2 - y_N^2 \end{cases} \qquad (4)$$

Finally, all but last equations (i = 1, 2, …, N-1) can be substituted to the last N-th formula:

$$2x(x_N - x_i) + 2y(y_N - y_i) = \\ = x_n^2 - x_i^2 + y_n^2 - y_i^2 - (d_n^2 - d_i^2) \qquad (5)$$

Because this is a linear equation, it can be represented in a matrix form:

$$AX = B \tag{6}$$

where:

$$X = \begin{bmatrix} x \\ y \end{bmatrix} \tag{7}$$

and:

$$A = \begin{bmatrix} 2(x_N - x_1) & 2(y_N - y_1) \\ 2(x_N - x_2) & 2(y_N - y_2) \\ \vdots & \vdots \\ 2(x_N - x_{N-1}) & 2(y_N - y_{N-1}) \end{bmatrix} \tag{8}$$

and:

$$B = \begin{bmatrix} x_N^2 - x_1^2 + y_N^2 - y_1^2 - (d_N^2 - d_1^2) \\ x_N^2 - x_2^2 + y_N^2 - y_2^2 - (d_N^2 - d_2^2) \\ \vdots \\ x_N^2 - x_{N-1}^2 + y_N^2 - y_{N-1}^2 - (d_N^2 - d_{N-1}^2) \end{bmatrix} \tag{9}$$

Finally, user position *X* can be calculated as:

$$X = A^{-1}B \tag{10}$$

III. Localization System Setup

The main criteria for choosing WLAN infrastructure is its cost-effectiveness. The selected hardware is easily available TP-Link TL-WDR3500 access point supporting both 2.4 and 5 GHz WLAN bands.

The investigated system has used 7 routers as APs and 1 router as users' receiver. The latter router had installed OpenWRT GNU/Linux distribution, which allowed readout of RSSI values. Wireless tools library for Linux has been used there with *iwlist* command, returning following data:

```
wlan0  Scan completed :
Cell 01 - Address: 00:12:17:46:A6:A4
ESSID:"NetworkName_1"
[[Protocol (computing)|Protocol]]:IEEE 802.11n
Mode:Master
Channel:1
Encryption key:off
...
Quality=82/100  Signal level=-48
```

The most important field is "*Signal level*" (in dBm units). Fields "*ESSID*" or "*Cell xx – Adress:*" have been used to identify corresponding AP.

Measured RSSI values from receiving AP have been decoded by Python script and *Paramiko* library:

```
ssh = paramiko.SSHClient()
ssh.set_missing_host_key_policy(paramiko.AutoAddPolicy())
ssh.connect( '192.168.1.1', username = 'root', password =
'password' )
stdin, stdout, stderr=ssh.exec_command( "iwlist wlan0 scan |
egrep 'Address|Quality'" )
```

User position has been calculated and visualized in Matlab environment:

```
for n=1:l
RSS(n,i) = dataArray(k,n);
  d(n,i) = 10^(-((RSS(n,i)-(-54))/(10*1.413)));
  if (d(n,i) > 12)
      d(n,i) = 10^(-((RSS(n,i)-(-54))/(10*1.832)))
  end
end
for p=1:(l-1)
  A(p,1) = [2*(x(l)-x(p))              ];
  A(p,2) = [               2*(y(l)-y(p))];
  B(p,i) = [(d(p,i)^2 - d(l,i)^2) - (x(p)^2 - x(l)^2) - (y(p)^2 -
y(l)^2)];
end
x0=A\B
```

The research aimed at proving that the usage of WLAN infrastructure (co-working as a location system) would not interfere with normal operation of network devices. The abovementioned TP-Link routers fulfilled the above criteria.

IV. Indoor Environment

Indoor tests have been performed in a laboratory room, which consists an elongated rectangular shape (15 m *x* 4.8 m) inside the university building. The structure is typical 60's construction: bricks, concrete and steel. The "upper" wall is fully windowed – fig. 3. The access points had no clean line of sight and large amount of wooden-metal obstacles (laboratory tables) in the middle of the area were significant difficulties for the system. However, it was possible to obtain useful location data. The indoor environment map is shown in the fig. 3.

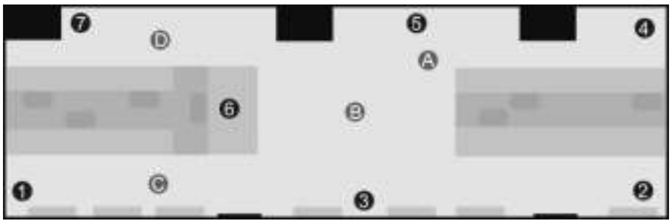

Fig. 3. Indoor room map.

A. *Static Location*

There have been measured positions of a four static test points (A-D). Their coordinates are presented in tab. 1. Static tests have been conducted for at least 50 measurements taken for each point. There have been used 6 APs as signal transmitters (standard *beacon frame*) at following locations shown in tab. 2.

Table 1. Indoor Coordinates of Test Points

	A	B	C	D
X [m]	9.4	7.75	3.85	3.85
Y [m]	3.7	2	1.4	5.4

Table 2. Indoor Coordinates of APs

	1	2	3	4	5	6	7
X [m]	0.6	14.55	8.4	14.55	9.7	5.8	0.65
Y [m]	0.35	0.35	0.4	4.3	4.6	2.4	4.6

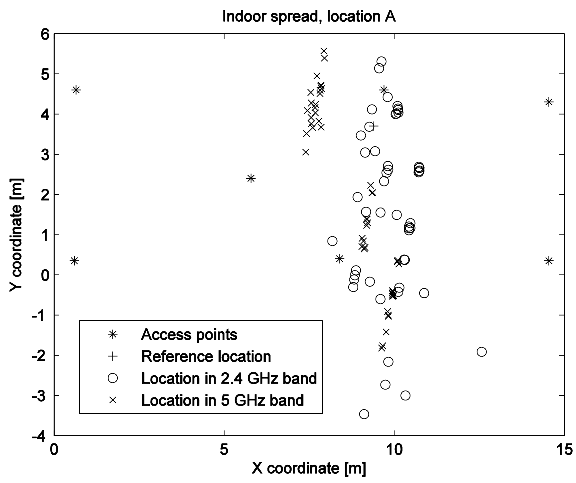

Fig. 4. Positioning spread at location A.

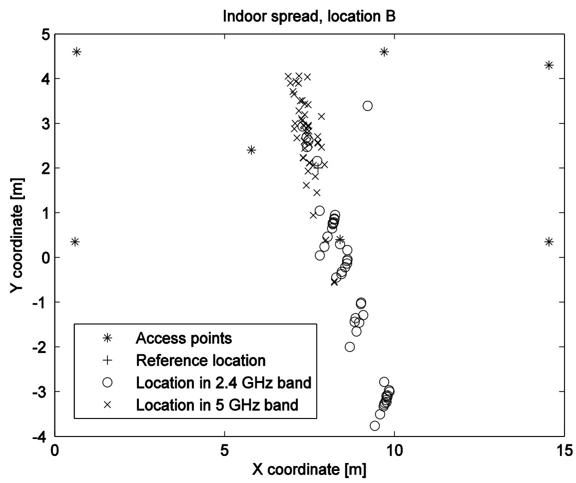

Fig. 6. Positioning spread at location B.

TABLE 3. LOCATION ERROR STATISTICS AT POINT A

Band [GHz]	*Error [m]*		
	Min.	*Average*	*Max.*
2.4	0.13	2.54	7.17
5	1.47	2.86	5.53

TABLE 5. LOCATION ERROR STATISTICS AT POINT B

Band [GHz]	*Error [m]*		
	Min.	*Average*	*Max.*
2.4	0.16	2.99	6
5	0.15	1.11	2.6

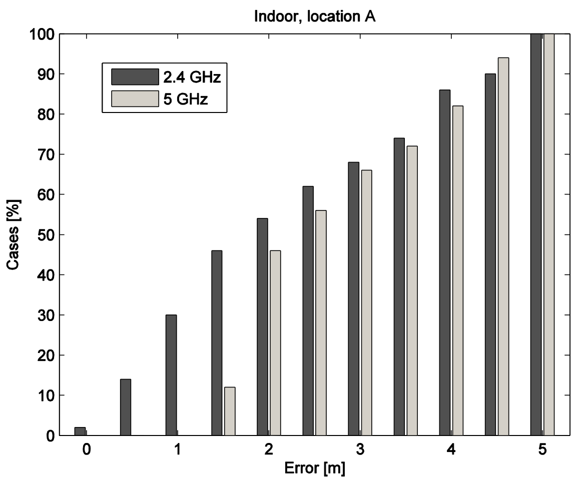

Fig. 5. Cumulative histogram of positioning error for location A.

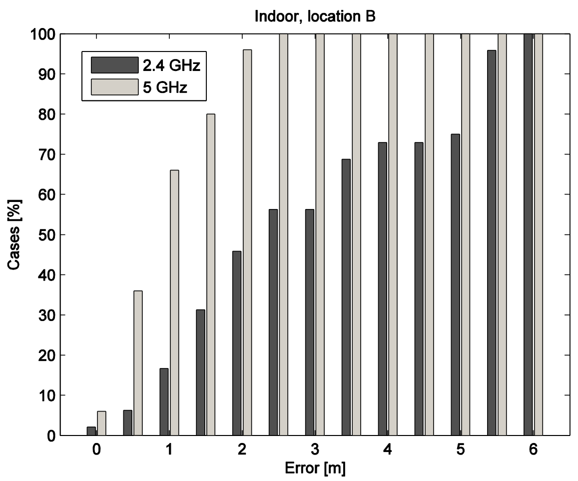

Fig. 7. Cumulative histogram of positioning error for location B.

TABLE 4. LOCATION ACCURACY FOR POINT A

Cases [%]	*Error [m]*	
	2.4 GHz band	*5 GHz band*
$\geq$ *50*	≤ 2	≤ 2.5
$\geq$ *70*	≤ 3.5	≤ 3.5
$\geq$ *90*	≤ 4.5	≤ 4.5

TABLE 6. LOCATION ACCURACY FOR POINT B

Cases [%]	*Error [m]*	
	2.4 GHz band	*5 GHz band*
$\geq$ *50*	≤ 2.5	≤ 1
$\geq$ *70*	≤ 4	≤ 1.5
$\geq$ *90*	≤ 5.5	≤ 2

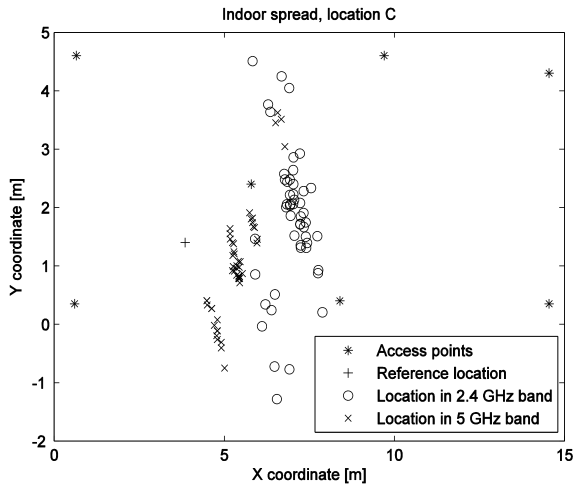

Fig. 8. Positioning spread at location C.

TABLE 7. LOCATION ERROR STATISTICS AT POINT C

Band [GHz]	*Error [m]*		
	Min.	*Average*	*Max.*
2.4	2.06	3.36	4.21
5	1.18	1.82	3.53

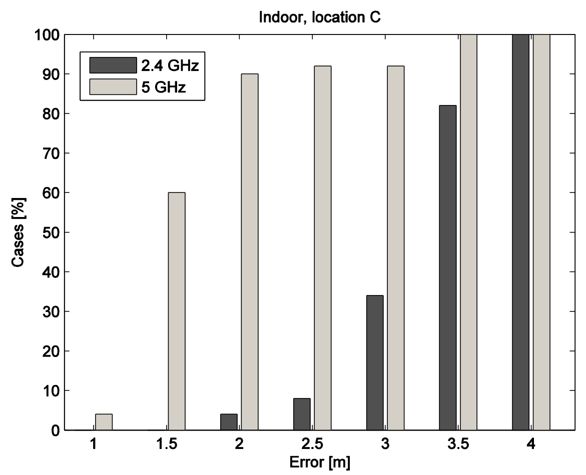

Fig. 9. Cumulative histogram of positioning error for location C.

TABLE 8. LOCATION ACCURACY FOR POINT C

Cases [%]	*Error [m]*	
	2.4 GHz band	*5 GHz band*
≥ 50	≤ 3.5	≤ 1.5
≥ 70	≤ 3.5	≤ 2
≥ 90	≤ 4	≤ 2.5

TABLE 9. LOCATION ERROR STATISTICS AT POINT D

Band [GHz]	*Error [m]*		
	Min.	*Average*	*Max.*
2.4	2.82	3.24	5.07
5	1.96	3.02	5.02

TABLE 10. LOCATION ACCURACY FOR POINT D

Cases [%]	*Error [m]*	
	2.4 GHz band	*5 GHz band*
≥ 50	≤ 3.25	≤ 3
≥ 70	≤ 3.25	≤ 3.5
≥ 90	≤ 3.5	≤ 4

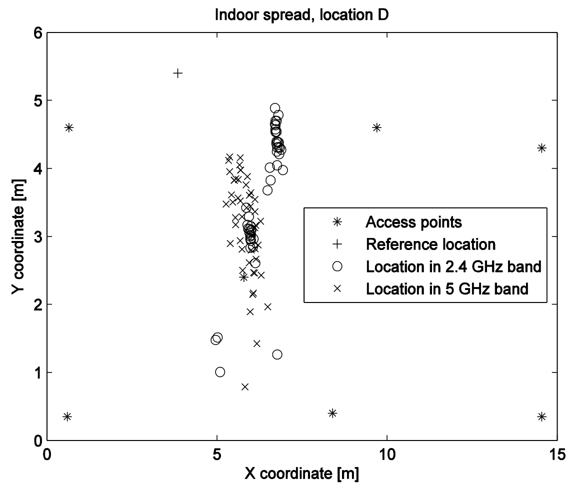

Fig. 10. Positioning spread at location D.

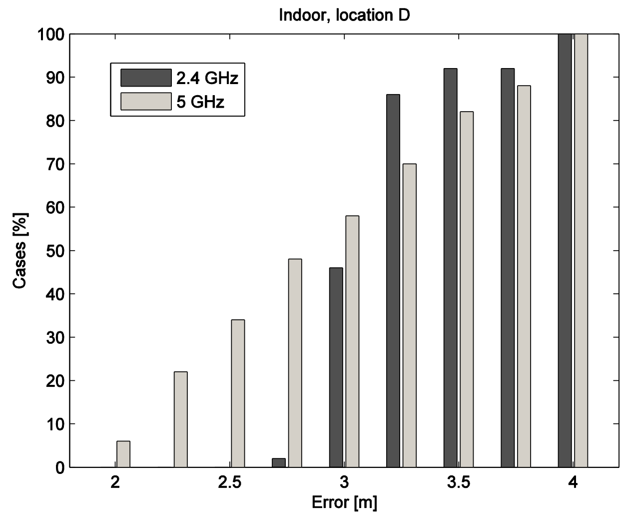

Fig. 11. Cumulative histogram of positioning error for location D.

There cannot be pointed clear winner for the above tests. Positioning at point A is performed more accurately in 2.4 GHz band (fig. 4,5; tab. 3,4), whether at points B and C in 5 GHz bands (fig. 6-9, tab. 5-8). Note that for all test cases, maximal location error is less than 6m. Possible error reduction could be obtained by eliminating locations outside the room.

B. Dynamic Location

Tests with user in motion were taken in both outdoor and indoor environments and in two previously mentioned frequency bands. The tests' purpose was to check the path tracking ability of the system. Plots present test environment, computed points and zones of correctness. The test area has been divided to three zones, which means points in that zone are (fig. 12):

- correctly computed – internal zone (dark),
- threshold values – middle zone (shadowed),
- incorrectly computed – outside the middle zone.

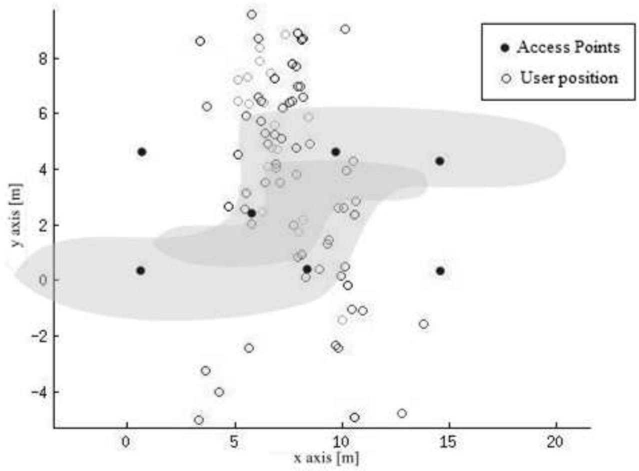

Fig. 12. Dynamic location for 2.4 GHz band.

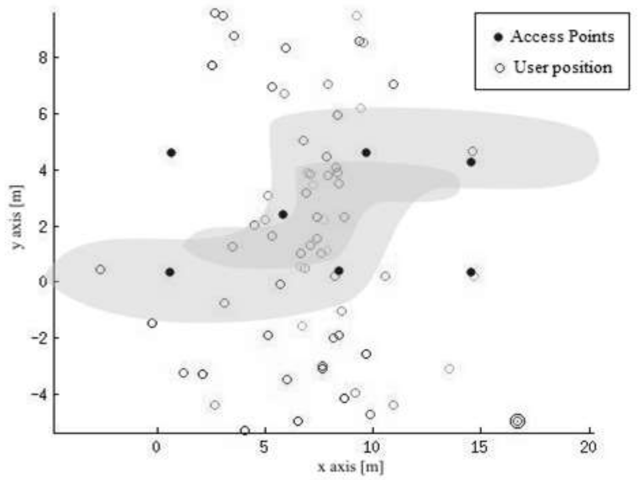

Fig. 13. Dynamic location for 5 GHz band.

TABLE 11. COMPARISON OF 2.4 GHZ AND 5 GHZ IN INDOOR PATH TRACKING ABILITY

Band [GHz]	*No. of points in particular "zones"*		
	Correct	*Threshold*	*Incorrect*
2.4	15	25	60
5	20	13	37

Results of this test show that location using 5 GHz band has an advantage over 2.4 GHz band – more points were added to first (correct) zone in indoor environment.

V. OUTDOOR ENVIRONMENT

Measurements in outdoor environment have been conducted between faculty building and a car park. Access points in the outdoor space had a clean line of sight communication, but the area was surrounded by small amount of trees. All APs have been places 130 cm above the ground level. The outdoor environment map is shown in the fig. 14.

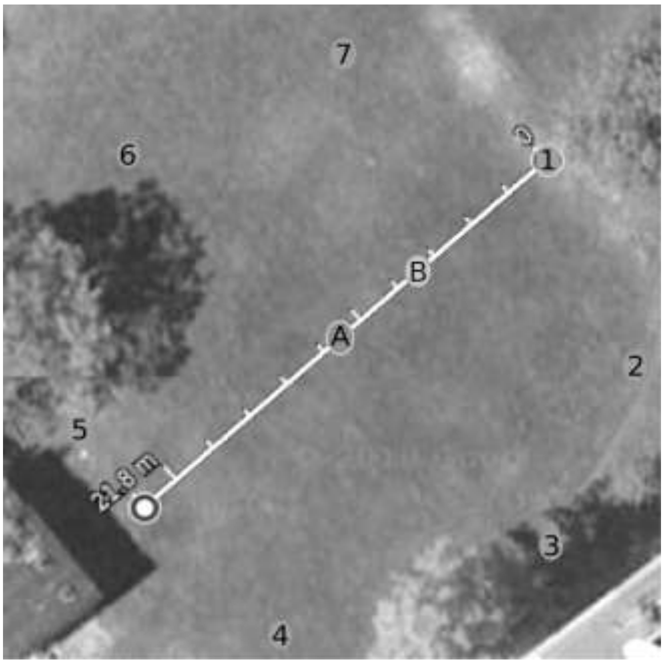

Fig. 14. Outdoor area map.

Coordinates of the access points are shown in table 12.

TABLE 12. OUTDOOR AP COORDINATES

	1	*2*	*3*	*4*	*5*	*6*	*7*
X [m]	0	2.75	8.9	21	21.8	14.75	4
Y [m]	13.5	3.75	0	4	16	23	22.25

Two different points, A and B, have been selected for static tests, with coordinates in the tab. 13.

TABLE 13. COORDINATES OF THE STATIC TEST POINTS

	A	*B*
X [m]	11.1	11.1
Y [m]	12.4	7.35

A. Static Location

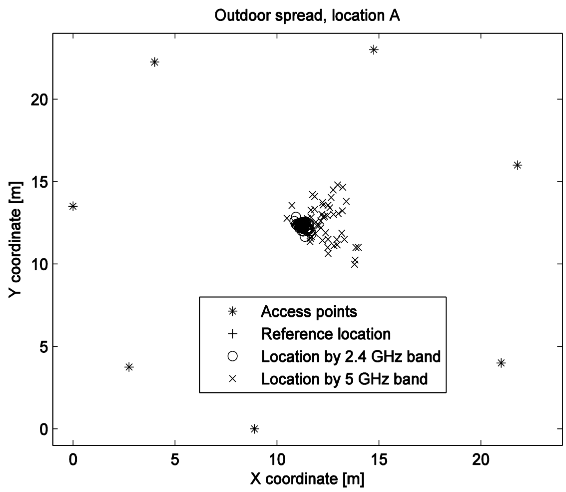

Fig.15. Positioning spread at location A (11.1, 12.4).

TABLE 14. LOCATION ERROR STATISTICS AT POINT A

Band [GHz]	*Error [m]*		
	Min.	*Average*	*Max.*
2.4	0.04	0.3	0.84
5	0.29	1.69	3.62

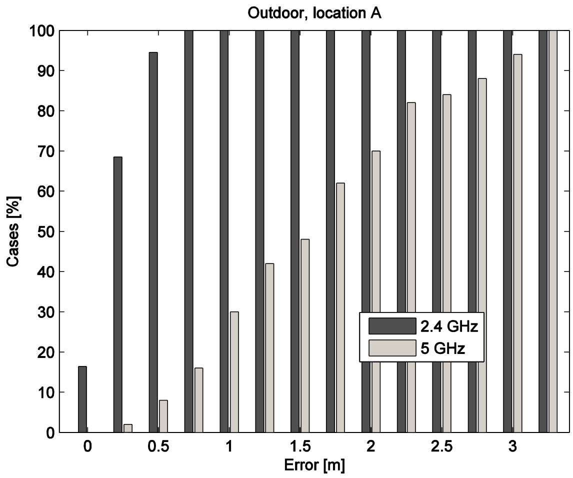

Fig.16. Cumulative histogram of positioning error for location A.

TABLE 15. LOCATION ACCURACY FOR POINT A

Cases [%]	*Error [m]*	
	2.4 GHz band	*5 GHz band*
≥ 50	≤ 0.25	≤ 1.75
≥ 70	≤ 0.5	≤ 2
≥ 90	≤ 0.5	≤ 3

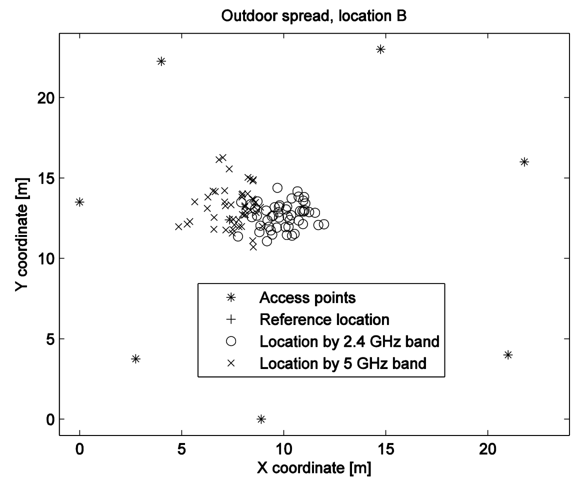

Fig.17. Positioning spread at location B (7.35, 12.4).

TABLE 16. LOCATION ERROR STATISTICS AT POINT B

Band [GHz]	*Error [m]*		
	Min.	*Average*	*Max.*
2.4	1.1	2.76	4.63
5	0.02	1.54	3.88

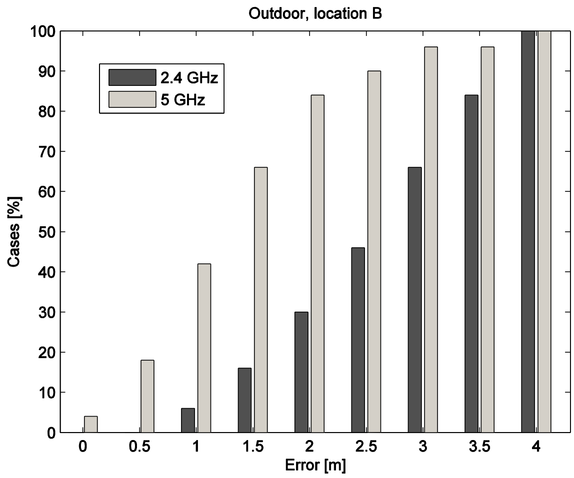

Fig.18. Cumulative histogram of positioning error for location B.

TABLE 17. LOCATION ACCURACY FOR POINT B

Cases [%]	*Error [m]*	
	2.4 GHz band	*5 GHz band*
≥ 50	≤ 3	≤ 1.5
≥ 70	≤ 3.5	≤ 2
≥ 90	≤ 4	≤ 2.5

Also in outdoor environment, there cannot be pointed clear winner for the above tests. Positioning at point A is performed more accurately in 2.4 GHz band (fig. 15,16; tab. 14,15), whether at points B and C in 5 GHz bands (fig. 17,18; tab. 16,17). Note that for all test cases, maximal location error is less than 4 m. Generally, closer similarity of outdoor environment to the used free-space propagation model resulted in higher location accuracy.

B. Dynamic Location

Tests with user in motion were repeated in outdoor environment (both bands). The test area has been divided to three zones, which means points in that zone are (fig. 19, 20):

- correctly computed – internal zone (dark),
- threshold values – middle zone (shadowed),
- incorrectly computed – outside the middle zone.

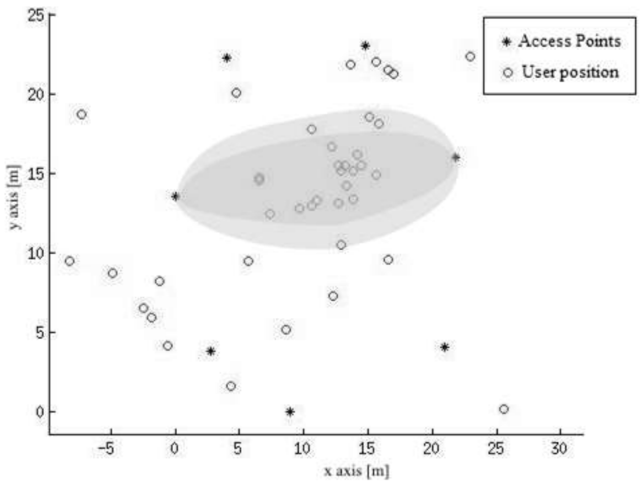

Fig. 19. Dynamic location for 2.4 GHz band.

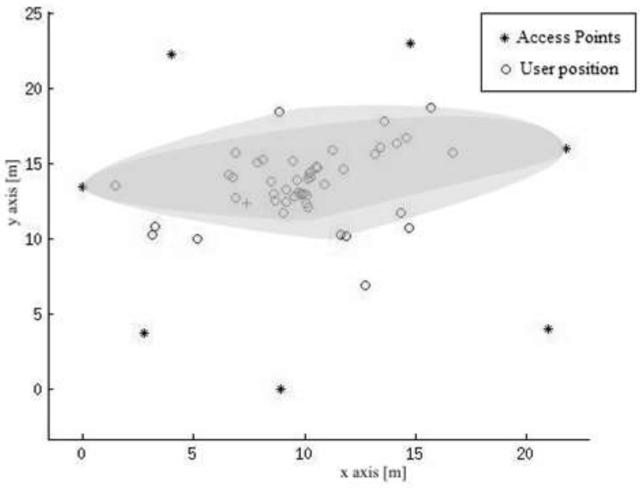

Fig. 20. Dynamic location for 5 GHz band.

TABLE 18. COMPARISON OF 2.4 GHZ AND 5 GHZ IN OUTDOOR PATH TRACKING ABILITY

Band [GHz]	No. of points in particular “zones”		
	Correct	Threshold	Incorrect
2.4	17	4	29
5	40	5	5

Results of this test show that outdoor tracking using 5 GHz band again has an advantage over 2.4 GHz band – more points were added to first (correct) zone in outdoor environment.

VI. CONCLUSIONS

No clear winner can be found both for indoor and outdoor environment. Depending on band, environment or particular location, positioning using 2.4 or 5 GHz band can be comparable or significantly different in terms of accuracy. Perhaps hybrid system could use strength of both bands, if only we know which one gives more accurate measurement at particular time.

Tracking moving object in 5 GHz band performed better than using 2.4 GHz band, especially outdoors.

The other problems influencing location accuracy were dense network communication in the 2,4 GHz band – especially indoor (fig. 21 and 22). Because details of calculating RSSI value are usually hidden by RF IC manufacturer (or weakly covered by documentation), influence of other channels and networks is difficult to take into account.

Other factors reducing positioning accuracy are low dynamics of RSSI readouts (approx. 60 dB) and its granularity. This can be observed as non-symmetrical and “jumping” spread over reference points. This and significant systematic error (shift) makes simple averaging techniques inefficient.

However, despite of above-mentioned problems and limitations, local positioning, both indoor and outdoor, using standard and unmodified WLAN infrastructure can be successful. Achievable accuracy of a few meters makes is still usable for middle-size non-critical applications: markets, commercial centers, museums, industrial zones etc.

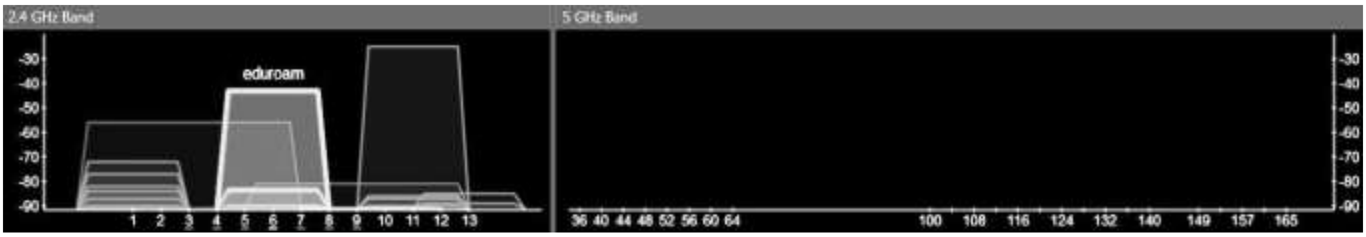

Fig.21. Interfering signals in indoor environment.

Fig. 22. Interfering signals in outdoor environment.

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