2021 International Conference on Circuits, Controls and Communications(CCUBE)

DESIGN OF A PORTABLE DF SYSTEM WITH SIMPLE AND COMPACT STRUCTURE OPERATING AT 875 MHZ GSM BAND

Mert Uludag
Student, Abdullah Gul University, Electrical and Electronics Engineering Department
Kayseri, Turkey
mert.uludag@agu.edu.tr

Ali Ozoksuzkaya
Student, Abdullah Gul University, Electrical and Electronics Engineering Department
Kayseri, Turkey
ali.ozoksuzkaya@agu.edu.tr

Veli Tayfun Kilic
Assist. Prof., Abdullah Gul University, Electrical and Electronics Engineering Department
Kayseri, Turkey
tayfun.kilic@agu.edu.tr

2021 International Conference on Circuits, Controls and Communications (CCUBE) | 978-1-6654-0203-3/21/$31.00 ©2021 IEEE | DOI: 10.1109/CCUBE53681.2021.9702722

Abstract—**This paper reports a portable GSM direction finding system operating at 875 MHz frequency band with simple and compact structure. In the system, array of receiver antennas are placed together with other RF components including amplifiers, power dividers, phase comparators, an analog to digital converter and a processor unit. With help of the developed algorithm phase comparison between the receiver antenna channels is obtained and angle estimation is done. The developed algorithm was first run on a constructed system test setup that involves a digital oscilloscope connected to the receiver antennas in a laboratory environment. Later, the digital oscilloscope in the test setup was replaced with the RF components mentioned above such that a portable receiver system with compact structure was obtained. Direction finding experiments were repeated with the designed portable receiver system in the laboratory and in open space. Results show that with the designed system angle of a transmitter is found very accurately such that the maximum angle error between the estimated and the exact angle values of the transmitter antenna was found to be equal to 3.5° in the open space experiments for the transmitter antenna positioned at an angle between -60° and 60° on the horizontal plane same with the receiver antennas. Also, it is observed that the difference between the estimated and the exact angle values has an increasing trend with the exact angle absolute value. The findings indicate that the designed portable direction finding system is promising to be used for applications requiring accurate angle estimation of GSM signals.**

Index Terms— **RF Direction Finding, Antenna Arrays, Portable System, 875 MHz GSM Frequency Band**

I. INTRODUCTION

Radio frequency (RF) direction finding is the process of capturing electromagnetic waves sent by a transmitter broadcasting in the RF frequency band or electromagnetic waves reflected from a target with help of receiving antennas and systems, and after a series of operations to estimate the direction of the transmitter or reflective target. RF applications have an important place in today's developing world in many different areas such as defense, communication and transportation [1, 2]. Also, RF direction finding is used in applications including radar systems [3], aircraft navigation systems [4], and GSM mobile communication systems [5].

GSM mobile communication systems such as cell phones became an indispensable part of people's daily life. With GSM direction finding location of a cell phone or a GSM signal transmitter and thus location of a person can be determined. Therefore, GSM direction finding systems are used in many different applications including finding a missing person in emergency situations [6] or detecting a cell phone indoors [7] such as in a secret meeting. Another possible application of GSM direction finding systems is locating a victim under debris. Unfortunately, humanity has experienced many disasters throughout the history. Earthquakes are one of the natural disasters. In earthquakes, some of the victims die immediately during collapse due to fatal injuries but others die after some time while waiting for help under the rubble. It is very critical to find and rescue those survivors under the debris as soon as possible. Usually the survivors need to be rescued within the first few hours or days, which are called golden hours and golden days, respectively [8, 9]. Different tools and methods have been used to find victims in disasters such as earthquakes, avalanches and landslides. For example, acoustic sensors are used to detect sounds and movements under a dent [10]. Although these tools and methods are very useful and lots of survivors were rescued with help of these tools and methods, they are not sufficient to detect survivors under debris all the time and exactly determine their locations. For example, the main disadvantage of using acoustic sensors is that the victim must have the ability to create a sound or move. If the victim is unable to create a sound at a certain level or move, then with the acoustic sensors it is not possible to determine the presence and location of the victim. In addition, in this method while searching with sensors, there should be no other sound and movement in the environment. This means that the rescue efforts in the area where a dent, avalanche or landslide occurred are completely stopped for a certain period of time.

In addition to the methods used for searching and detecting victims in disasters under debris, snow or soil, GSM direction finding is another method that can be applied to find victims. By capturing electromagnetic waves at GSM frequencies radiated from under debris, location of a victim can be determined. Unlike existing methods and devices used for detecting victims under debris, rescue operations can continue simultaneously with GSM direction finding. Also, GSM direction finding method is applicable together with other methods and devices, which enables easier and quick detection of a victim.

There are different GSM frequency bands used for mobile communication [6, 11]. In this study, a GSM direction finding system is designed to operate at 875 MHz frequency band, which is called 2G frequency band. The designed system performs best within this band only because of used components in the system The reason why 875 MHz frequency band was chosen is because of long wavelength with respect to other GSM bands. As the operating frequency increases wavelength decreases and it causes ambiguity problem [13]. Also, short wavelength results in physical sizes to be electrically long, which may cause wide spread of the electromagnetic wave and large decrease in wave intensity together with electromagnetic power. The designed system has a simple and compact structure and is portable. In the designed system array of receiving antennas are used and with phase comparison method direction finding estimation is done. Measurements were first obtained in laboratory environment with the designed prototype systems and then real time experiments were conducted in open space. Results show that direction finding at 875 MHz GSM frequency band is achieved with very high accuracy by using the designed system having very simple and compact structure.

II. METHOD AND SYSTEM DESIGN

In a direction finding system different methods are used including phase and amplitude comparisons. In our designed system, we preferred to use phase comparison method. In phase comparison method, direction of arrival and thus source of transmitted waves are determined by examining phase difference of the electrical signals received by the receiver antennas. Two receiver antennas placed next to each other together with an electromagnetic wave propagating towards the antenna at a certain direction are shown in Fig. 1.

In the figure, s and α represent distance between the antennas and the electromagnetic wave's angle of arrival, respectively. Also, path difference between the electromagnetic waves received by the antennas is shown with parameter d. As seen in the figure, path difference between the electromagnetic waves received by the antennas depends on both distance between the antennas and the angle of arrival. This relation is a very good approximation for fields radiated from far-field region. Although electromagnetic waves radiated from an antenna are usually spherical waves, in far-field they are like plane waves.

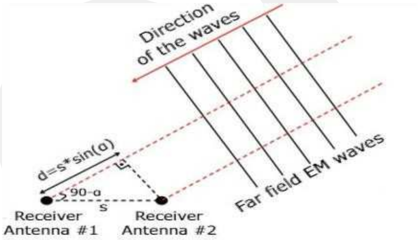

Fig. 1. An electromagnetic wave radiated towards two receiver antennas at a certain angle direction and the path difference between the waves received by the antennas.

The path difference between the received signals results in time and phase differences between the electrical signals produced in the receiver antennas [13]. Relations between the time and phase shifts of the electrical signals produced in the receiver antennas and the spacing between the antennas together with the angle of arrival and the operation frequency are given in equations (1)-(4).

$$\Delta t = \frac{d}{\lambda \cdot f} \tag{1}$$

$$\Delta\phi = \Delta t \cdot 2\pi f \tag{2}$$

$$d = \frac{\Delta\phi}{2\pi} \cdot \lambda \tag{3}$$

$$\alpha = \sin^{-1}\left(\frac{\Delta\phi}{2\pi} \cdot \frac{\lambda}{s}\right) \tag{4}$$

As in the figure, here s and α stand for the distance between the antennas and the angle of arrival of the incoming wave, respectively. Similarly, in the equations d represents path difference between the incoming waves. Also, in the equations Δt and ΔΦ are the time shift and phase difference between the electrical signals produced in the receiver antennas, respectively. Moreover, f is the operation frequency and λ is the wavelength of the incoming waves. In equation (4), it is clearly seen that in a designed system for a constant antenna spacing, one can find the angle of arrival by measuring the phase difference between the electrical signals if wavelength is known. Since wavelength equals to propagation speed of electromagnetic wave in the medium over frequency, by detecting frequency of the electrical signal wavelength is calculated easily.

As explained above, for direction estimation electromagnetic waves coming from a target must be received by antenna array consisting of multiple antennas and properties such as phase shifts of electrical signals produced on the receiver antennas must be compared. Although in direction finding systems usually accuracy of angle estimation increases with the number of the antennas, physical limitations, complexity of the receiver circuit, and increasing cost of the system restrict the number of receiving antennas in the array antenna. In our designed system setup we initially placed three receiver antennas on the same horizontal plane. The constructed system with three antennas on the same plane is shown in Fig. 2.

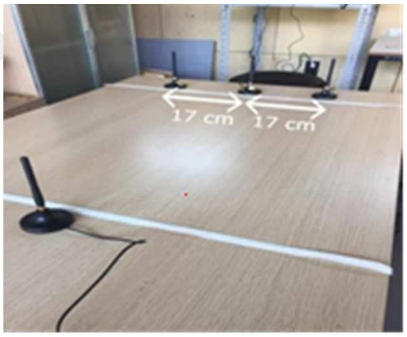

Fig. 2. Constructed direction finding system setup with three receiver antennas on the same horizontal plane.

As seen in the figure, in the system omnidirectional monopole antennas with 2 dBi gain are placed side by side with a constant distance of 17 cm. The used antennas are commercially available and cheap. Also, because of omnidirectional pattern of the antennas there is no expected difference on the received powers of the antennas resulting from antenna angular gain change. Therefore, received power level variations due to antenna pattern are not considered in the developed direction finding algorithm, which makes the process easier. On the other hand, the 17 cm distance between the antennas is chosen to be slightly lower than the half of the operating wavelength (λ ⁄ 2 = c ⁄ (2f) = (3×(10^8)) ⁄ (2×875×(10^6)) = 17.14 cm). By this way, it is aimed to avoid possible ambiguities in the angle estimations

[13].

After placing the receiver antennas as described, a transmitter antenna is located on the same horizontal plane with the receiver antennas at a distance far away from the receiver antennas such that the receiver antennas are in far-field region of the transmitter antenna at the operating frequency. In the system the omnidirectional antenna same with the receiver antennas is used for the transmitter antenna. Since antenna radiation occurs equally in all directions on the horizontal plane that the transmitter and the receiver antennas are placed, omnidirectional transmitter antenna usage results in received power independent from the direction of the transmitter antenna.

Later, direction finding algorithm was developed and with the constructed setup system tests were obtained. In the test setup, the transmitter antenna was connected to a signal generator. To model the GSM signal, a sinusoidal signal at 875 MHz frequency was generated by the signal generator and sent to the transmitter antenna. Resultantly, electromagnetic waves at 875 MHz frequency were radiated by the transmitter antenna during the tests. In the receiver side, on the other hand, the receiver antennas were connected to three channels of a four-channel digital oscilloscope. Electromagnetic waves received by the antennas were converted to electrical signals and in the constructed test setup these electrical signals were instantly recorded by means of the oscilloscope. The recorded electrical signals were then transferred to a computer and processed with the developed algorithm. Consequently, direction estimation was done. The transmitter and receiver sides of the test setup including the antennas, signal generator and digital oscilloscope are shown in Fig. 3a and Fig. 3b, respectively.

Although with the constructed prototype test setup measurements were made, it is necessary to develop the system for easy movement and being portable. In the constructed setup in the receiver side oscilloscope is not easy to move. Therefore, in the new system phase difference between the signals should be measured with another device instead of the oscilloscope. In the new system phase difference between the received signals of the receiver antennas is detected and measured by phase detectors. Schematic view of the new portable receiver system is shown in Fig. 4. As seen in the schematic the designed portable receiver system consists of three receiver antennas and each antenna output is first connected to a low-noise amplifier (LNA) and then to a 3 dB power divider. The LNAs amplify the signal level in each channel and increase the signal-to-noise ratio. The power dividers, on the other hand, are used to duplicate the output of the antennas. Outputs of each power divider are connected to input of different phase detectors and magnitude comparator. By this way, electrical signal coming from one channel, i.e., receiver antenna, is compared with signals coming from the other two channels separately. In the constructed system for phase detectors and magnitude comparator the same module is used.

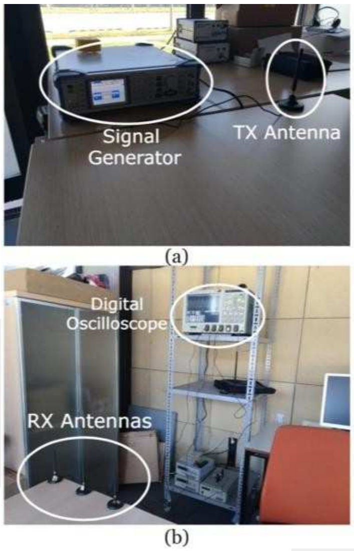

Fig. 3 Constructed direction finding system setup with the antennas on the same horizontal plane. (a) Transmitter side with the transmitter antenna connected to the signal generator, (b) receiver side with the three receiver antennas connected to three channels of the four-channel digital oscilloscope.

The used module has 2 SMA inputs and 2 analog outputs corresponding to the phase and magnitude differences between the input signals. In the design, phase comparisons are made between the first and second channels together with the second and third channels. In the system it is not necessary to measure the phase difference between the first and third channels because it can be found by adding the measured phase differences between the first and second channels, and the second and third channels. On the other hand, as seen in the figure magnitude comparison is made between the first and third channels in the designed system.

Since the second channel corresponds to the receiver antenna at the center and the first and third channels correspond to the receiver antennas at the two sides, with magnitude comparison between the first and third channels it is determined whether the electromagnetic wave comes from the first receiver antenna side or it comes from the third receiver antenna side. This is a new independent data and used with the measured phase data in the system. Outputs of the phase detectors and magnitude comparators are analog signals thus they are connected to and digitalized by an analog to digital converter (ADC) in the system. Digital signals at the output of the ADC are processed by a processor unit with help of the developed direction finding algorithm and angle estimation is done.

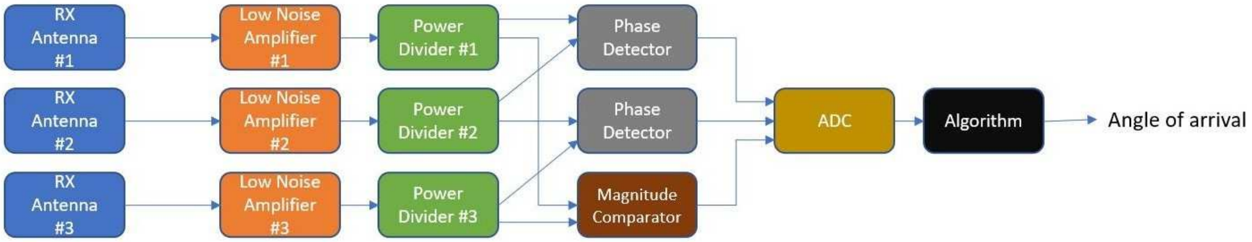

Fig. 4. Schematic view and the parts of the portable receiver system designed for direction finding process.

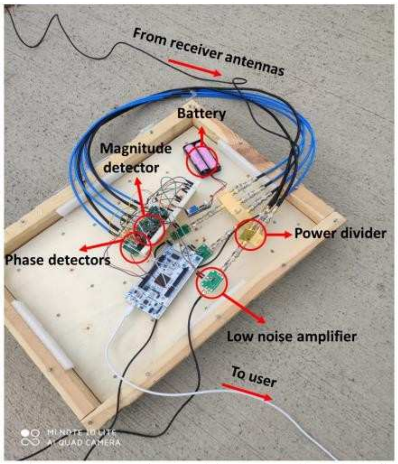

Fig. 5. Produced compact and portable GSM direction finding receiver system and its parts.

III. EXPERIMENTS AND OBTAINED RESULTS

Experiments were conducted with the designed prototype system (see Fig. 2 and Fig. 3) and the produced portable system (see Fig. 5), respectively, in the laboratory environment and open space.

As it is described in method and system design part, in the experiments conducted with the prototype system the transmitter antenna was connected to the signal generator and the receiver antennas were connected to three channels of the four-channel digital signal oscilloscope. To model a GSM signal a sinusoidal signal at 875 MHz was generated by the signal generator and radiated by the transmitter antenna. With help of the developed algorithm by measuring phase difference between the electrical signals on the receiver antennas direction finding and angle estimation were achieved. The experiments were repeated for the transmitter antenna positioned at different angles between -90° and 90° with respect to the receiver antennas on the same horizontal plane with the receiver antennas. In Table I angle estimation values obtained with the prototype system and the exact angle of the transmitter antenna in each case are given together with the angle error.

TABLE I. ANGLE VALUES OBTAINED WITH THE PROTOTYPE SYSTEM IN THE LABORATORY EXPERIMENTS

Test number	**Measurement Results**		
	Exact angle value (degree)	*Measured angle value (degree)*	*Angular error (degree)*
1	-90	-87.2	2.8
2	-80	-82.7	2.7
3	-70	-68.4	1.6
4	-60	-62.0	2.0
5	-40	-38.5	1.5
6	-30	-31.4	1.4
7	-10	-8.0	2.0
8	0	0.6	0.6
9	10	11.4	1.4
10	30	32.5	2.5
11	40	41.3	1.3
12	70	72.1	2.1
13	80	83.1	3.1
14	90	88.9	1.1

In the table it is seen that the absolute difference between the found and the exact angle values has an increasing trend with the exact angle absolute value. The maximum error was found to be equal to 3.1° for the transmitter antenna located at 80° angle with respect to the receiver antennas. For clear understanding and better representation absolute angle error change with exact angle of the transmitter antenna found in the experiments is shown on a half pie chart in Fig. 6. In the figure, increase in the angle error with the transmitter antenna's angular position is clearly seen.

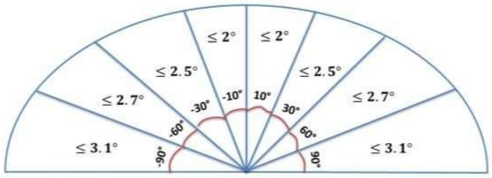

Fig. 6. Absolute angle error change with angle of the transmitter antenna measured in prototype system experiments in the laboratory.

Next, measurements were repeated with the produced compact and portable receiver system again in the laboratory environment. As explained above, in the new system instead of the digital oscillator signal comparisons are made with help of the phase and magnitude comparators, ADC, and processor unit. On the other hand, as in the previous experiments, the transmitter antenna was connected to the signal generator and to model a GSM signal a sinusoidal signal at 875 MHz was generated and sent to the transmitter antenna. Again, experiments were repeated for the transmitter antenna placed at different angular positions with respect to the receiver antennas on the same horizontal plane. Angle estimation values found in the experiments and the exact angle values of the transmitter antenna together with the angle errors are given in Table II.

TABLE II. ANGLE VALUES OBTAINED WITH THE PRODUCED COMPACT AND PORTABLE RECEIVER SYSTEM IN THE LABORATORY EXPERIMENTS

Test number	**Measurement Results**		
	Exact angle value (degree)	*Measured angle value (degree)*	*Angular error (degree)*
1	-90	-109.0	19.0
2	-70	-53.0	17.0
3	-60	-54.9	5.1
4	-50	-54.7	4.7
5	-40	-36.8	3.2
6	-30	-26.9	3.1
7	-10	-8.9	1.1
8	0	1.1	1.1
9	10	11.3	1.3
10	20	22.7	2.7

11	30	29.5	0.5
12	60	56.4	3.6
13	70	58.6	11.4
14	90	68.4	21.6

Absolute value change of the angle error found in the experiments with the angle of the transmitter antenna is displayed on a half pie chart in Fig. 7.

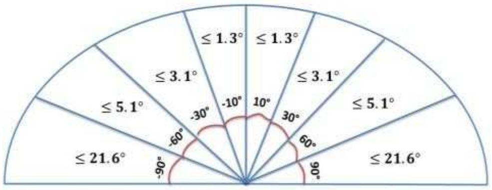

Fig. 7. Absolute angle error change with angle of the transmitter antenna measured in portable receiver system experiments in the laboratory.

In the figure it is also seen that for the electromagnetic waves coming with an angle bigger than 60°, i.e., the transmitter antenna positioned at an angle bigger than 60° with respect to the receiver antennas, the estimated angle deviates too much from the exact direction. One of the reasons of observing high angle deviation might be possible reflections occurred in the laboratory environment. Such reflections may cause interference of the waves and also they may affect the produced RF system.

To prevent possible reflections in the laboratory environment, experiments were repeated with the produced compact and portable receiver system in open space. In the experiments again to model a GSM signal a sinusoidal signal at 875 MHz was generated by the signal generator and sent to the transmitter antenna. Photo of the receiver system with the receiver antennas connected to the system and the transmitter antenna located far away from the receiver antennas on the same horizontal plane in open space is shown in Fig. 8.

The outside experiments were repeated for the transmitter antenna positioned at different angles.

Estimated angles found in the experiments and the exact angle values that the transmitter antenna is positioned together with the angle errors are given in Table III. As in the previous experiments, in Table III it is seen that the difference between the estimated angle values and the exact angle values has an increasing trend with the exact angle absolute value. In addition, as similar within the in laboratory experiments of the produced portable receiver system, in open space experiments obtained angle error values are still high for the transmitter antenna positioned at angles outside the -60° and 60° angle interval. This is not expected and it indicates that the produced portable GSM direction finding system performance is low for the incoming waves coming from angles beyond the specified angle interval not because of possible reflections in the environment.

On the other hand, if the angle error values given in Table II and Table III are compared it is seen that the absolute angle error values except the one found for -10° exact angle in the angle interval of -60° and 60° are lower in the open space experiments than those obtained in the laboratory experiments.

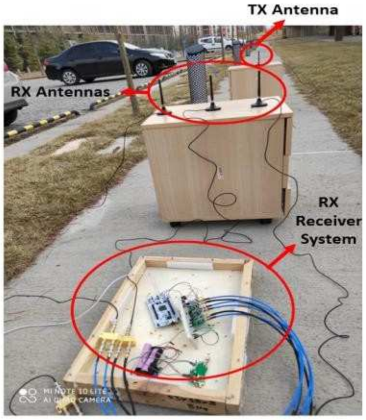

Fig. 8. Photo of the receiver system captured during experiments with the receiver antennas connected to the receiver system and the transmitter antenna on the same horizontal plane in open space.

It demonstrates that the produced portable GSM direction finding system performance in the angle range from -60° to 60° increases further by preventing possible reflections in the environment. Absolute value change of the angle error found in the open space experiments with the angle of the transmitter antenna is represented on a half pie chart in Fig. 10.

In the chart it is seen that the estimated angle differs from the exact angle of the transmitter antenna, i.e., direction of the incoming waves, by 3.5° at most in the open space experiments if the TX antenna is located at an angle between -60° and 60°.

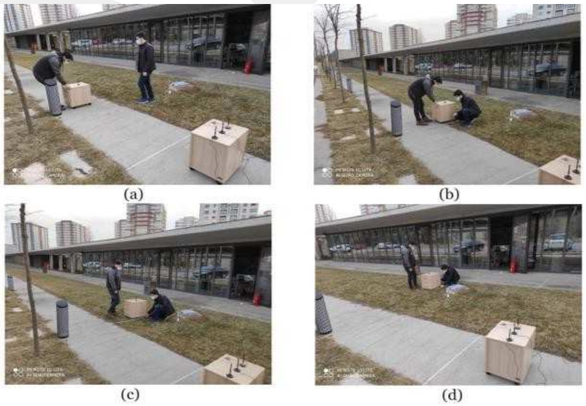

Fig. 9. Photos taken during the experiments in which the transmitter antenna is located at (a) 0°, (b) 15°, (c) 30°, and (d) 45°angle measured from the direction directly opposite the receiver antennas.

TABLE III. ANGLE VALUES OBTAINED WITH THE PRODUCED COMPACT AND PORTABLE RECEIVER SYSTEM IN THE OPEN SPACE EXPERIMENTS

Test number	**Measurement Results**		
	Exact angle value (degree)	*Measured angle value (degree)*	*Angular error (degree)*
1	-90	-68.1	21.9
2	-80	-94.6	14.6
3	-60	-63.5	3.5
4	-50	-52.8	2.8
5	-40	-39.1	0.9
6	-30	-32.0	2.0

7	-20	-20.6	0.6
8	0	0.8	0.8
9	10	9.7	0.3
10	20	22.2	2.2
11	30	30.3	0.3
12	50	48.9	1.1
13	60	56.8	3.2
14	90	105.0	15.0

It is worth to note that the distance between the transmitter and receiver antennas was around 5 m in the experiments and it was successfully increased up to 12 m in outdoor experiments.

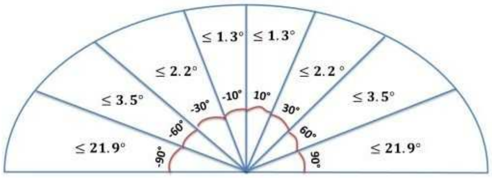

Fig. 10. Absolute angle error change with angle of the transmitter antenna measured in portable receiver system experiments in open space.

IV. CONCLUSION

In this study, a portable GSM direction finding system with a simple and compact structure operating at 875 MHz frequency band is designed. Initially, a prototype system was built with the receiver antennas connected to channels of a digital oscilloscope and a transmitter antenna connected to a signal generator in the laboratory environment. In the experiments to model a GSM signal a sinusoidal signal at 875 MHz frequency was generated by the signal generator and sent to the transmitter antenna. For the transmitter antenna positioned at different angles experiments were repeated and phase differences were measured between the channels of the oscilloscope. Results show that with the developed direction finding algorithm applied to the constructed prototype test system setup direction estimation is achieved with 3.1° maximum error for the transmitter antenna positioned within 180° angle interval between -90° and 90° on the same horizontal plane with the receiver antennas. Next, constructed system was developed further with placement of RF components that are amplifiers, power dividers, phase detectors, and ADC. In the system phase differences between the receiver antenna signals are detected with phase detectors and the developed algorithm is run on the processor. The laboratory experiments were repeated with the developed portable receiver system and measurements were performed again for the transmitter antenna positioned at different angles with respect to the receiver antennas on the same horizontal plane. It is found that the angle error value equals to or is lower than 5.1° for the transmitter antenna positioned within the 120° angular range between -60° and 60°. However, outside the specified range the angle error value increases very rapidly.

As in the laboratory experiments, in open space experiments estimated angle value deviates more from the exact angle value as the exact angle absolute value gets bigger. On the other hand, it is seen that the angle error values except the one found for -10° exact angle in the interval of -60° and 60° are lower in the open space experiments than those found in the laboratory experiments. This is an expected result and demonstrates the performance increase of the designed system with reduction of reflections in the environment. In the open space experiments for the transmitter antenna positioned at an angle between -60° and 60°, difference between estimated angle and the exact angle values is found to be 3.5° at most, which is lower than the 5.1° maximum angle error found in the laboratory experiments. Also, to model a real scenario better, for future studies it would be nice to repeat the experiments with obstacles between the transmitter and the receiver antennas, which may result in changes in system performance due to possible reflections, refractions and diffractions.

V. ACKNOWLEDGEMENTS

This project work was supported by TUBITAK within the scope of "TUBITAK 2209-A University Students Research Projects Support Program".

REFERENCES

[1] Dowla, F., Handbook of RF and Wireless Tehcnologies, Elsevier Inc., 2004.

[2] Y. Cai and R. C. Liu, "Application of RF tags in highway reference markers," 2008 11th International IEEE Conference on Intelligent Transportation Systems, 2008, pp. 464-469, doi: 10.1109/ITSC.2008.4732619.

[3] E. Fishler, A. Haimovich, R. Blum, D. Chizhik, L. Cimini and R. Valenzuela, "MIMO radar: an idea whose time has come," Proceedings of the 2004 IEEE Radar Conference (IEEE Cat. No.04CH37509), 2004, pp. 71-78, doi: 10.1109/NRC.2004.1316398.

[4] G. Miko and A. Nemeth, "Combined communication and radio navigation system for small UAVs," 2013 23rd International Conference Radioelektronika (RADIOELEKTRONIKA), 2013, pp. 284-287, doi: 10.1109/RadioElek.2013.6530932.

[5] S. L. Preston, D. V. Thiel, T. A. Smith, S. G. O'Keefe and J. W. Lu, "Base-station tracking in mobile communications using a switched parasitic antenna array," in IEEE Transactions on Antennas and Propagation, vol. 46, no. 6, pp. 841-844, Jun. 1998, doi: 10.1109/8.686771.

[6] R. Sarkis, C. Craeye, A. Ferreol and P. Morgand, "Design of triple band antenna array for GSM/DCS/UMTS handset localization," 2009 3rd European Conference on Antennas and Propagation, 2009, pp. 3051-3054.

[7] J. Xiong and K. Jamieson, "Arraytrack: a fine-grained indoor location system," Proceedings of the 10th USENIX Conference on Networked Systems Design and Implementation (NSDI'13), 2013, pp. 71-84, doi: 10.5555/2482626.2482635.

[8] Y. Lien, H. Jang and T. Tsai, "A MANET based emergency communication and information system for catastrophic natural disasters," 2009 29th IEEE International Conference on Distributed Computing Systems Workshops, 2009, pp. 412-417, doi: 10.1109/ICDCSW.2009.72.

[9] J. B. Fenn, N. P. Alfano and G. P. Young, "Method and apparatus for activating an emergency beacon signal," United States Patent US 9591466 B2, Mar. 7, 2017.

[10] H.Ye, "Life detection technique in earthquake search and rescue," 2012 Second International Conference on Instrumentation, Measurement, Computer, Communication and Control, 2012, pp. 664-666, doi: 10.1109/IMCCC.2012.161.

[11] S. Yildiz, S. Kilinç, A. Aksen and S. B. Yarman, "Dual Band Filter Design for GSM Bands Using Frequency Mapping and Real Frequency Technique," 2018 18th Mediterranean Microwave Symposium (MMS), 2018, pp. 164-167, doi: 10.1109/MMS.2018.8612080.

[12] Martino, A. D., Introduction to Modern EW Systems, Artech House Radar Library, 2012.

[13] J. Lee, J. Lee and J. Woo, "Method for obtaining three- and four-element array spacing for interferometer direction-finding system," in IEEE Antennas and Wireless Propagation Letters, vol. 15, pp. 897-900, 2016.