EJTAS
ISSN 2786-7447
EUROPEAN JOURNAL OF THEORETICAL AND APPLIED SCIENCES
OPEN ACCESS
PEER REVIEWED

Design and Optimization of a 2.4 GHz Antenna Array for Energy Harvesting

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Suggested Citation
Nnamdi, U., Omijeh, B. & Asianuba, I. (2023). Design and Optimization of a 2.4 GHz Antenna Array for Energy Harvesting. *European Journal of Theoretical and Applied Sciences, 1*(6), 676-683.
DOI: 10.59324/ejtas.2023.1(6).67

Abstract:

In this paper, a 2.4GHz antenna array for wireless power transfer (WPT) was designed and optimized for energy harvesting using MATLAB Software. Antennas are essential communication tools in energy harvesting systems as such; they are used to transmit and receive signals. The designed antenna is a 2 x 4 microstrip array. The choice of the microstrip antenna stems from the fact that, it is a class of patch antenna which satisfies all low-level conditions for Radio frequency (RF) transmission. Array antennas are deployed to maximize the overall gain, improve signal reception and achieve excellent performance. The antenna specifications were used in the analysis of the antenna formulations. The simulation result obtained shows satisfactory parameters for energy harvesting. The maximum gain was improved from 17.0 dbi to 17.5 dbi after optimization. The reflection co-efficient was also maintained above a magnitude of -26.2db. The antenna also recorded low correlation co-efficient. With the growth of self-sustaining devices, antenna arrays for energy harvesting provides an innovative solution for ecofriendly technologies.

Keywords: *Antenna arrays, Patch, Gain, MATLAB, Energy Harvesting.*

Introduction

Wireless power transmission (WPT) can solve the constraints of wired power supply and has shown great potential in areas like wireless charging, sensor networks, etc. (Glaser, 1968; Yi et al., 2020). WPT technology can be applied on sensors installed on motor shafts, because cabling becomes challenging with aa motion over time. However, it can further be applied on objects that need costly maintenance or are challenging to access, such as remote sensors in dangerous locations. In a WPT system, the antennas are used to transmit and receive power in free space (Peng et al., 2022). In order to transmit wireless power, a number of antennas can be utilized, each with its unique benefits and drawbacks. For instance, omnidirectional antennas transmit power evenly in all directions, though at a lower energy density, while directional antennas provide a much narrower field of view but at a higher energy density. The deployment scenario affects the choice and placement of antennas. For instance, since there is no need to move and focus the beam to other receivers with a one-to-one setup, directional antennas can be very effective. However, a multi-channel omnidirectional array with a wider field of view would be advantageous in a multi-receiver scenario in order to direct energy to particular a receiver. Akin to the transmission side, the installation orientation and required gain are taken into consideration when choosing receiver antennas. Omnidirectional antennas don't need to be pointed in any particular direction, whereas directional antennas must be aimed in the direction of the transmitter to get the best results. RF power can be combined with multiple channel receiver antenna arrays to drive heavier loads. Antenna arrays can be used to enhance the efficiency of the system in each of the operating regions because of the ability to scan and focus beams (Ibrahim et al., 2020). It increases the overall gain, provide diversity reception, reduces interference and maximizes the signal to interference plus noise ratio (SINR).

Microstrip Antennas for RF Energy Harvesting

Microstrip antenna are metallic patches, that can be in various configurations or designs on a grounded substrate. The rectangular and circular patch are the most popular designs because of easy fabrication and analysis, low cross polarization and interesting radiation characteristics (Chaour et al., 2018; Ifeoma & Lucky, 2022). Other designs are sometimes deployed like the trapezoid. A square half-wave patch antenna is required for ranges of 7-8dB (Bensky, 2019). The microstrip antenna is versatile in application due to its polarization, resonant frequency, impedance, and radiation pattern (Pozar, 1992). A rectangular microstrip patch element is shown in Figure 1. The patch element lies on top of a bigger rectangular ground plane.

The patch element and the ground plane are separated by the substrate material. The width W, length L, height h, and dielectric constant of the substrate define the dimensions of a rectangular microstrip antenna. Typically, the dielectric constant ranges between 2.2 and 12 (Kushwah & Tomar, 2011). The substrate of the microstrip element is carefully selected to ensure good performance and an optimal patch element size. Antenna with low dielectric constant and thick substrate provide superior performance, high efficiency and larger bandwidth. In this situation, the patch size increases, and so the antenna size grows. Microwave circuitry requires a higher dielectric constant and a thin substrate. They provide close bound fields, reducing unwanted radiation and coupling.

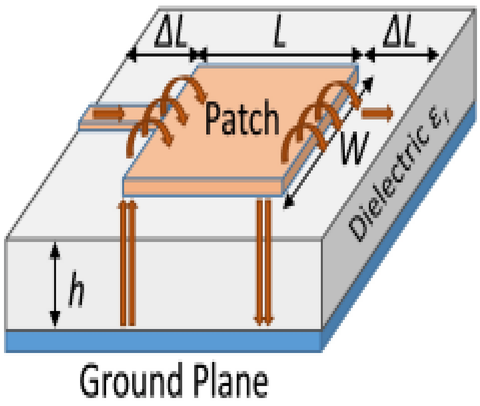

Figure 1. Simple Microstrip Patch Element

The antenna size has been lowered. However, as a result of the resulting losses, the antenna efficiency drops and the bandwidth narrows.

Review of related works

Casu et al., (2014) designed and implemented two 4x1 and 8x1 patch antenna arrays at an operating frequency of 2.4GHz using IE3D software and a dielectric material FR4 with dielectric substrate permittivity of 4.28, tangent loss of 0.002 and height of 1.6 mm. It was designed for WLAN applications.

The authors in (Abubakar, et al., 2021) deigned at 2.45Ghz and simulated three different microstrip patch antenna arrays using CST. The performance characteristics of the antenna patch arrays elements 1X2, 1X4 and 2X2 were compared. The gains of the different arrays were compared, and the 1 x 4 array was the highest at 8.5dB.

In (KANBOZ & PALANDÖKEN, 2023) microstrip patch antenna with dual bands was designed for RF energy harvesting systems. The antenna operated at 2.4 and 5.2Ghz. The simulation gave antenna gains of 1.6dBi and 3.95dBi at different resonant frequencies. The designed antenna parameter values such as bandwidth, VSWR and reflection coefficient were satisfactory for energy harvesting.

The design of a small 1X2 microstrip patch antenna array that is excited via the corporate feed technique is shown in the work (Swathi et al., 2023). The proposed antenna is built on a FR-4 substrate that has a thickness of 1.6 mm and a dielectric constant of 4.4. High frequency simulation software is used to compute the dielectric constant and other factors such as return loss, gain, and radiation pattern. The outcomes of the simulation should be compared with the constructed antennas. The 2.4 GHz frequency range is intended for this antenna.

(Sharma & Saini, 2016) designed and fabricated a microstrip four- patch antenna array to harvest energy from the GSM 1800 band. The antenna is simulated using HFSS software. It has a return loss of -25dB and a high gain of 9.2dB. In (Chaour et al., 2018), a patch antenna operating at 2.4GHz is proposed for energy harvesting. The Ansoft HFSS simulator was used to develop the proposed antenna based on the RT/duroi 5880 substrate. First, the patch element was tuned as part of the antenna design process. A low return loss of -23.9 dB is obtained with a high gain of 17.2 dBi. It is acceptable that the antenna input impedance is around 44 **Ω**. This design's 52.2 MHz limited bandwidth is its primary flaw.

In (Sharma et al., 2018), a patch antenna array operating at 1800 GSM band with 9.2dBi gain was developed for energy harvesting circuit. The antenna worked within the 1810-1880MHz frequency. A return loss of -25dB was obtained. The gain was observed at a resonant frequency of 1.8GHz. However, there was a slight shift in central frequency from 1.8 to 1.7GHz. (Rajawat & Singhal, 2018) designed a dual band rectifier antenna operating at 900MHz and 2.4GHz frequencies for energy collection. The proposed antenna is a microstrip U slot antenna with S11 parameter less than -10dB. It also has a gain of 5.1 dBi and 10.1 dBi at 900 MHz and 2.45 GHz, respectively.

(Sultana et al., 2016) introduced a dual patch circular antenna with a direct feed through microstrip feed line to operate at 1.95GHz and 2.45GHz. A good radiation characteristic is achieved by placing a reflection plane behind the antenna at optimal position. The antenna has gain of 8.3 and 7.8dBi at 1.95 and 2.45 GHz, respectively. (Silva et al., 2020) proposed a double Patch Antenna Array (DPA) composed of two patch antennas operating at different frequencies and fabricated on a unique substrate. The first one operates at 1.8GHz for mobile communication while the second one works at 2.4GHz industrial, scientific and medical band and used for Radio Frequency Energy Harvesting.

(Olowoleni et al., 2021) developed and simulated a novel three-point star antenna and compared it to the conventional square microstrip antenna design. Both designs operated at 2.4GHz and were accessed in terms of gain, directivity, return loss, radiation pattern, and efficiency. From the simulation results, the proposed "3-point star" design, though slightly less efficient showed a better performance over the conventional square patch alternative, in terms of gain, directivity, and return loss.

Antenna Formulation

The design choice of an antenna array was made haven considered its parametric characteristics. Directivity, size, ease of manufacture, resilience, and efficiency were some of the most important variables that necessitated the choice. The design of the antenna arrays was implemented using MATLAB 2022 edition. The patch antenna was utilized for the antenna design because, when properly designed, it meets all low-level specifications for sending and receiving microwave energy. There is a feed-line conductor trace, (in this case copper), that links the transmission circuitry to the copper patch. This is region foe which energy goes in or out of the transmission and receiving antennas, respectively. There are numerous antenna feed-lines that can be employed in microwave transmission. Some of the factors examined for selecting the feed-line type were simplicity of manufacture, bandwidth effects, and efficiency at 2.4 GHz. The microstrip provides adequate gain and has a moderate broad bandwidth. The antenna was first designed using a thorough set of equations that dictated the characteristics of rectangular microstrip antennas. The design equations were adopted from Antenna Theory and Design according to (Balanis, 2005). In order to calculate the patch sizes of the antenna operating at the targeted frequency, several parameters must be determined beforehand. These are the antenna's resonance frequency,"fo", the substrate thickness "h", and the dielectric constant of the substrate material "εr

The width of the patch antenna is computed using the following formulas:

$$\text{Patch width } W = \frac{c}{2f_0}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

The Length of the microstrip patch antenna is given by the equation:

$$\text{Patch Length } L = \frac{C_0}{2f_0\sqrt[2]{\varepsilon_{reff}}} - 2\Delta L \quad (2)$$

$$where\ \varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+12\frac{h}{w}}}\right] \quad (3)$$

$$\varepsilon_{eff} = \text{Effective dielectric constant} \quad (4)$$

and

$$\Delta L = 0.412\ x\ h\ x\ \frac{E_{reff}+0.3}{E_{reff}-0.258}\ x\ \frac{\frac{w}{h}+0.264}{\frac{w}{h}+0.8} \quad (5)$$

The subarray design was carried out using full-wave electromagnetic simulations to allow for the optimization of the return loss and gain of the subarray. The low loss substrate, Rogers RO4003 (ϵ_r= 3.38), with thickness of 1.52 mm was used. The parameters for the antenna arrays are given in the tables below. $\Delta L = Length\ Extension$.

Table 1. Dimension of a Single Microstrip Array

Substrate length (SL)	60mm
Substrate width (SW)	77mm
Substrate thickness (SL)	35mm
Patch Length (PL)	29.5mm
Patch Width (Pw)	38mm
Microstrip Length (ML)	SL/2 – PL/2
Microstrip Width (MW)	2.86mm
Inset Length dimension (INL)	9mm
Inset Width dimension (INw)	0.745mm

Table 2. Dimensions for the Properties of the Rectangular Array

Array size	2,4
Row spacing (m)	0.089334
Column Spacing (m)	[0.089034 0.089185 0.08911]
Lattice	Rectangular
Amplitude Taper	1V
Tilt Axis	[0 0 1]

The design frequency was set to 2.4 GHz, with a 2-by-4 array dimension. To examine the antenna arrays, the accept button on the MATLAB 2022a interface was activated. The rectangular array of microstrip patch antennas and the geometry at 2.4 GHz in the array and layout 3D radiation pattern were then observed. The column and row spacing of the antenna array is 0.088 m, and the tilt axis is [0 0 1]. The array's maximum gain is 17.5 dBi. The front-to-back lobe ratio was calculated using a 2-D elevation pattern. The following input parameters are necessary to optimize an antenna array using an inverted coplanar patch antenna array.

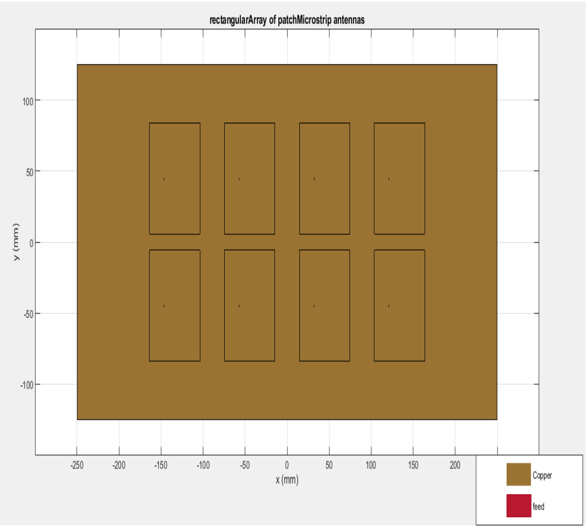

Figure 2. 3D layout of the 2 X 4 Antenna Antenna optimization

- Objective function: The optimization's principal purpose. The objective function evaluates the analysis function and optimizes its output.

- Design variables: These are the input variables that must be optimized in order to attain the goal function within specific limits. The optimizer changes the variables within a predefined range of values known as the variable boundaries.

- Constraints: The requirements under consideration that must be met. The limitations are entirely optional. If there are numerous requirements, the user can use the % weight option to prioritize the constraints.

- Other factors considered: These inputs could include the number of iterations, the center frequency, and the frequency range throughout which the analysis is run.

Results and Discussions

Return Loss: The return loss of the antenna is represented by the antenna's reflection coefficient S-parameter characteristic (S11). The S11 parameter is one of the most used metrics for evaluating antenna performance. It refers to the amount of incident power that is reflected by the antenna. The antenna resonance frequency is achieved at 2.4GHz. The reflection loss coefficient value at the resonance frequency is -26.2dB, indicating a good impedance match condition. The bandwidth of the designed antenna is 96MHz making it suitable for wireless power transfer application.

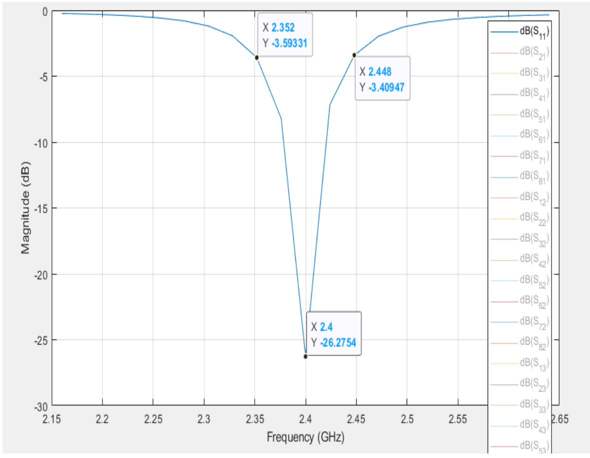

Figure 3. S11 Parameter of the antenna

Correlation Coefficient: In the context of antenna arrays, correlation coefficients are often used to evaluate the performance and characteristics of the array, especially in applications like beamforming and spatial processing. The antenna correlation coefficient (ACC) is a critical antenna metric that measures the independence of nearby antennas. The lower the ACC, the more the independence of the antennas from one another. The antenna correlation coefficient of the elements of the proposed antenna is very low. Figures 4,5,6 shows some of the values between various elements. The values are 0.00890697, 0.00470682 and 0.0119694 respectively.

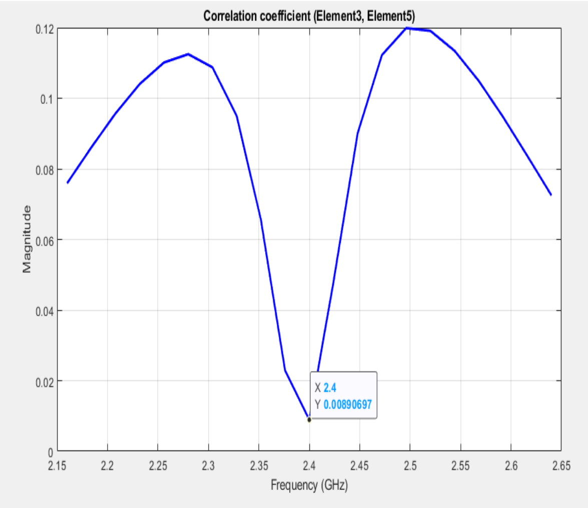

Figure 4. Correlation Efficient between Elements 2 and 3

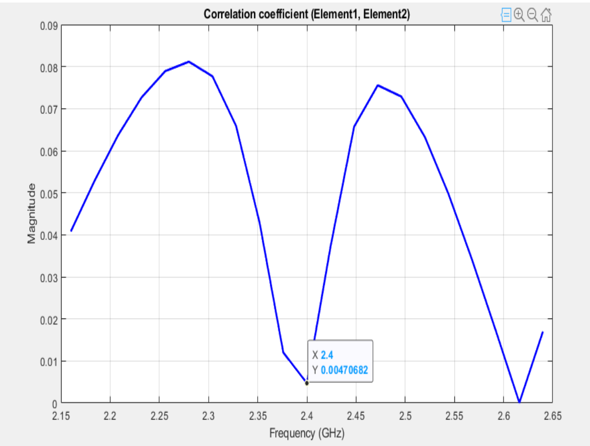

Figure 5. Correlation Efficient between Elements 1 and 2

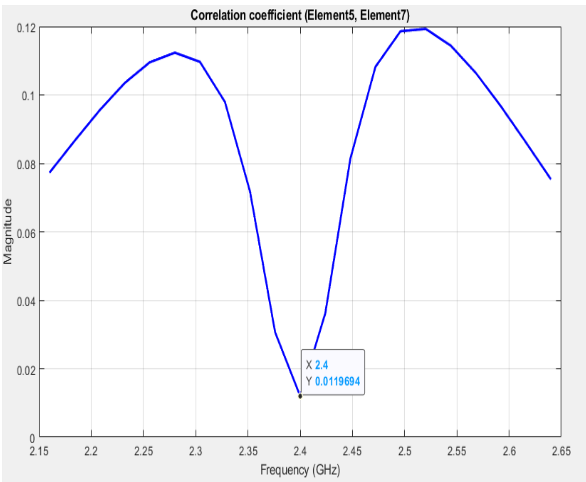

Figure 5. Correlation Efficient between Elements 5 and 7

Gain and Radiation Pattern: The gain of an antenna describes its efficiency and directional capabilities. The gain of an antenna array can be described as the ratio of the intensity in a given direction to the radiation intensity produced if the same power was radiated using one isotropic radiator. The antenna array proposed in this work has a gain of 17dBi and 17.5dBi after optimization. It means that the output power or intensity is 17.5 dB greater than the input power or intensity. So, the output signal will be about 31.62 times more powerful than the input signal if converted from the logarithmic scale (dB).

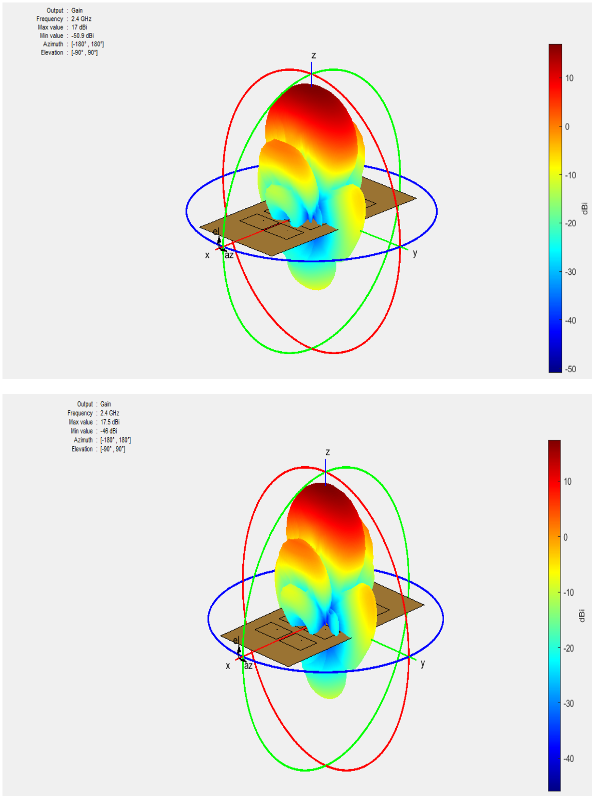

Figure 6. 3D radial Pattern of Antenna Gain Before and After Optimization

Figure 7 shows the elevation and azimuth pattern of the antenna. The azimuth plane pattern is measured when the measurement is made traversing the entire x-y plane around the antenna under test. The elevation plane is then a plane orthogonal to the x-y plane, say the y-z plane. The sidelobe levels from different angles especially in the azimuth pattern are all less than

-10db which is the minimum standard. This shows that the antenna can be used to transmit electromagnetic signals.

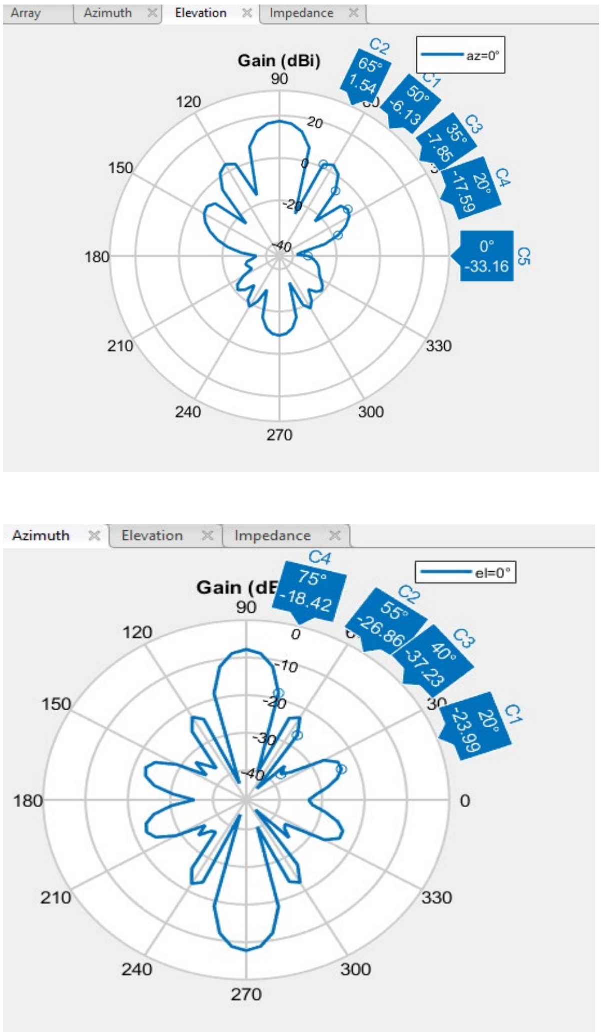

Figure 7. Elevation and Azimuth pattern of the antenna

Table 3. Comparison between parameters before and after optimization

Antenna parameters	Before optimization	After optimization
Column spacing (m)	0.080	0.089
Row spacing (m)	0.080	0.089
Gain (dBi)	17.0	17.5

Conclusion

The issue of low gain by single element antennas is addressed in this paper. The design of 2 X 4 microstrip patch antenna arrays for energy harvesting is presented. The simulation of the designed antenna was done using MATLAB 2022. The antennas performance characteristics such as return loss, gain and correlation coefficient were obtained in the simulation. The simulation result obtained shows satisfactory parameters for energy harvesting. It has an S11 parameter of -26.2dB and a gain of 17.5dBi. The S11 is above the standard of -10dB for microstrip antennas. The correlation coefficients between the elements were also very low which shows very small dependences between the antenna elements. This also indicates good coupling. As a result, it can be used in RF energy harvesting applications with the designed antenna combiner, rectifier and matching circuits. However, the side lobe levels of the antenna can be further worked on to ensure better transmission of signals.

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