# Designing Ultra-low-power Cardiac Pacemaker with Quantum Cellular Automation Technology

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Received: April 2021 Revised: May 2021 Accepted: July 2021

**ABSTRACT:**
The heartbeat is triggered by a sinoatrial node in the heart. If the sinoatrial node is disrupted for any reason or if there is a problem with the heart's electrical signal path, the heart rate will decrease or become impaired; in which case the cardiac pacemaker could control the heart function. The pacemaker is an electrical stimulator that causes the heart to expand and contract and triggers pulses to the heart when needed or permanently. Since the pacemaker is placed inside the patient's body, it should be designed based on the minimum power consumption. Besides, frequency adjustment in this device is necessary to regulate heart rate in a variety of arrhythmias. In this paper, logic cells of quantum cellular automata are utilized to design a pulse generator circuit in a heart oscillator, where power consumption and dimensions are minimal. An important feature of the proposed circuit is the ability to adjust the output pulse frequency. The efficiency of this circuit has been evaluated using QCAdesigner simulator and desirable results have been obtained in terms of power consumption level. The simulation results also show very low power consumption for the designed circuit.

**KEYWORDS:** Pacemaker, Quantum Cellular Automata, QCA designer, Simulation.

## 1. INTRODUCTION

According to Moore's Law, the size of transistors in electronic circuits is halved every two years. As the number of transistors in integrated circuits (the smaller the transistors) increases, fewer electrons and holes for electrical conduction travel a shorter path, and thus the information processing speed increases.

Nowadays there are limitations against reducing the size of transistors one of which is the quantum effect that affects all nanometer aspects in the CMOS technology and hinders the continued development of this technology [1]. Quantum cellular automata (QCA) is one of the emerging technologies that offers a new way of digital processing as a branch of nanotechnology. Since QCA has provided significant progress in the design of digital gates at the nanoscale with minimal power consumption, it is necessary to evaluate and use this technology in various fields. The QCA technology was introduced by Lent in 1993 and has been the subject of extensive theoretical and laboratory research ever since [2]. This technology determines the logic of zero and one circuit based on the displacement of electric charge inside the cell; therefore, only the displacement of electrons (instead of creating current by electrons), could have a significant effect on reducing power consumption in the circuit [3].

The pacemaker is one of the circuits that must be designed with the least power consumption. This device, which is designed in different ways according to the patient's needs, generates a suitable electrical signal that can be applied to the heart when necessary or permanently [4]. The human heart normally has 60 to 100 beats per minute, which is generated by an atrial sinus node in the heart. If there is a disorder in the sinus node or there is a problem in the electrical signal path of the heart for any reason, the heart rate decreases or is disturbed, in which case the pacemaker can control the heart's main function [5, 6]. The pacemaker is a small device that is placed near the heart in the upper chest area under the patient's skin by the surgeon and its electrodes enter into the heart through the vessels [7]. Fig. 1 shows the approximate location of the pacemaker in the body [7]. Pacemakers last for almost ten years, which depends on the type of battery and the disease. In patients with persistent heart arrhythmia, the battery creates impulse permanently. In such cases, it is necessary to design a



Paper type: Research paper
DOI: https://doi.org/10.52547/mjtd.10.3.105
How to cite this paper: M. Mahdavi, M. A. Amiri, "**Designing Ultra-low-power Cardiac Pacemaker with Quantum Cellular Automation Technology**", Majlesi Journal of Telecommunication Devices, Vol. 10, No. 3, pp. 105-110, 2021.

circuit to reduce power consumption, and the QCA is one of the proposed candidates for circuit design with minimal power consumption [8].

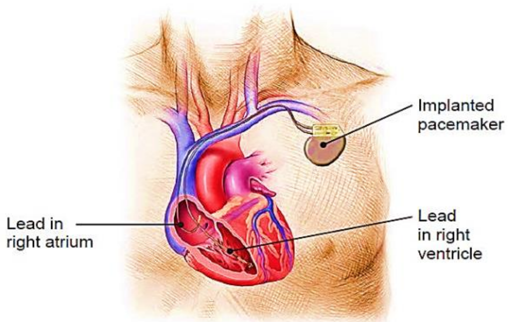


**Fig. 1.** Approximate location of the pacemaker in the body [7].

The human heart beats an average of about 100,000 times a day, and usually, the heart's electrical stimulation cells accumulate in its connective tissues. Between the two atria, only the right atrium has a nodular tissue called the Sinoatrial node, which is located in the posterior wall of the right atrium and under the inferior vena cava. For contraction, first, the Sinoatrial node is stimulated spontaneously and rhythmically and directs this contraction message through three strands of the right atrial node to the ventricular atrial node, located between the walls of the atria and ventricles and slightly inclined to the right atrium. Then the ventricular node tissues propagate this electrical wave stimulation throughout the ventricles. All cells in these nodal tissues have a basal rhythmic rate; however, because the number of Sinoatrial node beats per minute is higher, they send stimulus waves (usually 70 to 100 beats per minute) to stimulate the tissues faster than their basal rhythm. Therefore, other heart cells are not normally pacemakers and only the Sinoatrial node is a pacemaker. Thus, the heart has several potential cells that cause oscillation spontaneously [6].

In the early twentieth century, many experiments were performed, including drug therapy and electrical pacing of the heart to resuscitate the patient from cardiac arrest. The early methods used to stimulate the heart electrically applied a current that caused the heart muscle to contract. "The purpose of the electric shock is to provide a controllable excitatory point at which a stimulus wave may travel back and forth around the heart in its normal path," said Albert Hyman. Hyman designed the first experimental pacemaker in 1932 [9].

Electrocardiography is the recording of electrical activity produced by the heart that is measured on the surface of the body. The electrocardiogram was first proposed by Waller in 1899 [4]. Einthoven (1903) introduced electrophysiological concepts, including ECG-specific wave labeling, which are still used today [10]. He attributed the letters P to U to the waves, thus distinguished them from other physiological waves studied at the time [11, 12]. Fig. 2 shows the signal of a typical ECG. The ECG signals are usually in the range of ±2 mV and have a bandwidth of 0.05 to 150 Hz. The morphology of ECG waves depends on the amount of tissue activated per unit time and the relative rate and direction of cardiac activity [10]. Early pacemakers, regardless of any spontaneous activity of the heart, simply applied a constant rate pulse to the ventricle at a predetermined frequency. These pacemakers called asynchronous or fixed-rate pacemakers compete with normal heart activity and can sometimes even cause cardiac arrhythmias [4].

By adding a sensor amplifier to the asynchronous pacemaker to detect the innate activity of the heart and thus prevent competition, the pacemaker applies electrical stimuli to the heart only in the absence of a normal heartbeat. Another advantage of these pacemakers over the fixed-rate system is that the battery life of this system is long and the reason is that these pacemakers are activated only when the pulse is required. The most common pacemakers use a lithium battery or similar, and another type has an atomic battery that lasts longer and is more expensive. In one type of this device, a nickel-cadmium battery is used, which is recharged every week by placing a device on the patient's chest, which creates problems for the patient [13].

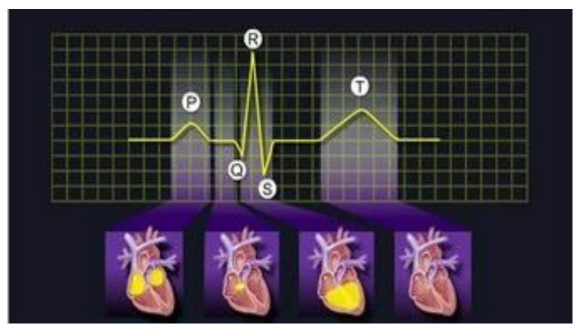


**Fig. 2**. The signal of a typical ECG

In an arrhythmia, the patient develops a condition in which the normal heartbeat produces an abnormal rate, or when the normal signaling pathways of the heart are interrupted, other parts of the heart control the rhythm and improper oscillation happens. An artificial pacemaker can return the required synchronization. The pacemaker exerts a controlled rhythmic electrical stimulus on the heart muscle [14]. So far, oscillators have been designed analog by an operational amplifier or a transistor, so that the output is feedback to the input through a filter that acts as a frequency selector for the pulse generator circuit to generate positive feedback. First, when the power supply is connected, it generates an electrical noise, this noise rotates in the loop, and it is amplified by the amplifier to be converted into a waveform with the appropriate frequency. The analog circuit initially becomes unstable using positive feedback and increases the oscillation amplitude; however, this increase in amplitude stops at certain amplitude and it will have stable oscillation amplitude [15]. The main purpose of this paper is to model the pulse generating circuit in a pacemaker using QCA technology. A distinctive feature of this technology, in addition to a significant reduction in power, is the reduction of circuit dimensions to below microns. The rest of this article is organized as follows. Section 2 presents an overview of the QCA and the pulse generating circuits. Section 3 offers the pulse generator design method based on the proposed design and its simulation using QCAdesigner simulator. The results are presented in section 4 and Section 5 concludes the paper.

## 2. A REVIEW OF THE QCA TECHNOLOGY

In the QCA, a cell has four quantum dots located in the four corners of a square and it looks like Fig. 3. Quantum dots are places where electrons can be placed. Each cell has two additional electrons that can be placed in the four corners of the square, but due to the repulsive forces between the electrons, they are only allowed to be at a maximum distance from each other thus they will occupy diameter cells and will have respective polarizations as p=-1 (logic “0”) and p= +1 (logic “1”) as shown in Fig. 3. Polarization of the cells is calculated by equation (1) [1],

$$P= ((\rho1+\rho3)-(\rho2+\rho4))/(\rho1+\rho2+\rho3+\rho4) \qquad (1)$$

The basic logic gates in this technology are designed based on the interaction between cells. These gates include the logic inverter gate and the logic majority gate which are shown in Fig. 4 and Fig. 5. The logic majority gate consists of 5 cells. The logic AND gate can be implemented with the majority logic gate and setting one of its inputs to zero logic. The logic OR gate can be implemented with the logic majority gate and setting one of its inputs to logic 1 [16].

Clocking in QCA provides a mechanism for the simultaneous movement of data in the circuit. The clock also controls the direction of data movement in QCA circuits and provides the power required to operate the circuit. More precisely, the QCA clock is used to control the height of the tunneling barriers in the cells. When the clock level is low, the electrons are trapped in their respective positions and cannot tunnel to other quantum dots, thus the reasonable cell value is maintained.

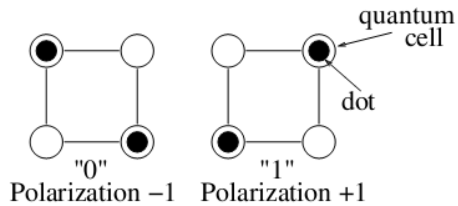


**Fig. 3**. QCA cell

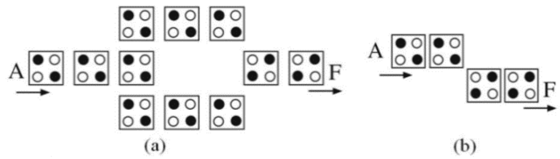


**Fig. 4**. Inverter gates

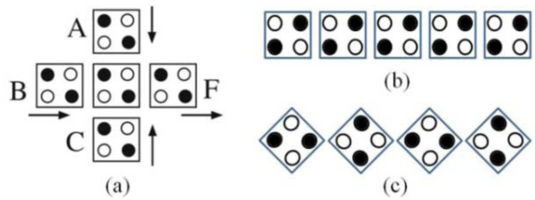


**Fig. 5**. (a) Majority voter, (b) Binary wire, (c) $45^0$ wire

Fig. 6 shows the clocking function. When the clock level is high, the cell will go into hold state. In this state the cell in fully polarized and maintains a logic value. When the clock level is low, the cell will go into relax state. In this state the cell in not polarized and doesn’t have a logic value. Between these two states, the cells are either latching or relaxing. Each cell in the clock zone is connected to one of the four phases of the clock and the clock is latched or unlatched with the changes in the signal; therefore, the data are transmitted through the cells [16] [17] [2].

## 3. THE PROPOSED PULSE GENERATOR

Structurally, a pacemaker consists of at least three parts: the electrical pulse generator, the power source, and the electrode (conductor), which is shown in Fig. 7 [18].

The electrical connection between the heart and generator circuit is established by an electrode called a lead. Depending on the various types of diseases, different types of output pulses can be used to stimulate the heart. The stimulus signal which is generated by the pulse generator will be applied to the heart as an electrical charge. For an effective stimulation, the output pulses must have sufficient width and energy to stimulate cardiac cells close to the electrode. The pacemaker uses the energy stored in the batteries to stimulate the heartbeat.

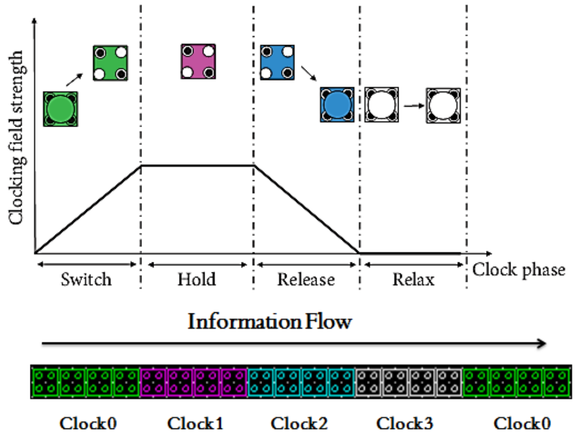


**Fig. 6**. QCA clock zones.

The electric pulse generator consists of the following components: a sensor amplifier circuit, timing control circuit, and output driver circuit (electric shock). The schematic model of the proposed circuit implemented with the QCA technology is shown in Fig. 8. As shown in Fig. 8, the feedback loop is generated by the inverter gate, which will generate the main oscillation signal. This feedback helps to apply logic one to the inverter gate after a delay if the input gate input is zero at the beginning. The placement of several delay cells has been used to generate the delay required to detect the edges of the generated pulse. The output of the delay circuit detects the edges of the generated pulse by its invert and an AND gate. To make the system programmable, the activator base, which is turned into AND with the output of the circuit, is utilized. This base allows activating the system only when needed, and at other times when the base is zero, the output will be zero as well.

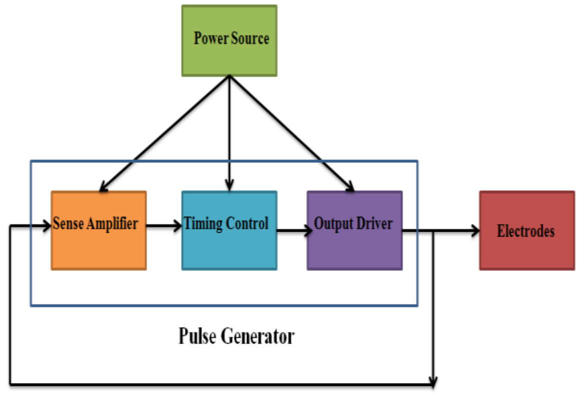


**Fig. 7**. Pacemaker parts.

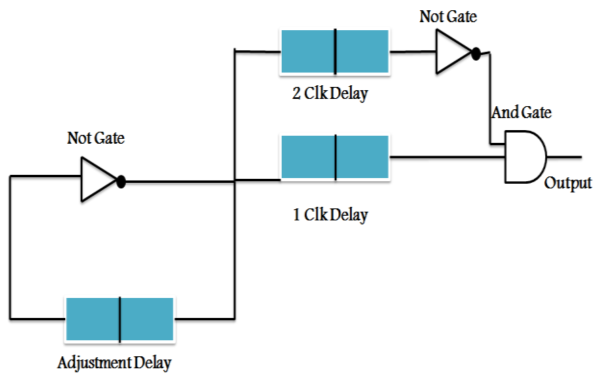


**Fig. 8.** The schematic model of the proposed circuit.

An important feature of this circuit is that the output pulse is adjustable, which means that the output signal width can be adjusted according to the coefficients of the input clock pulse. This is possible with different outputs provided by the circuit with different delays. This circuit can also be used to generate a wide frequency range from a few hertz to kilohertz. As shown in Fig. 9 implemented with QCADesigner simulator [19], by changing the length of the connecting wires, it is possible to produce different signals with different widths.

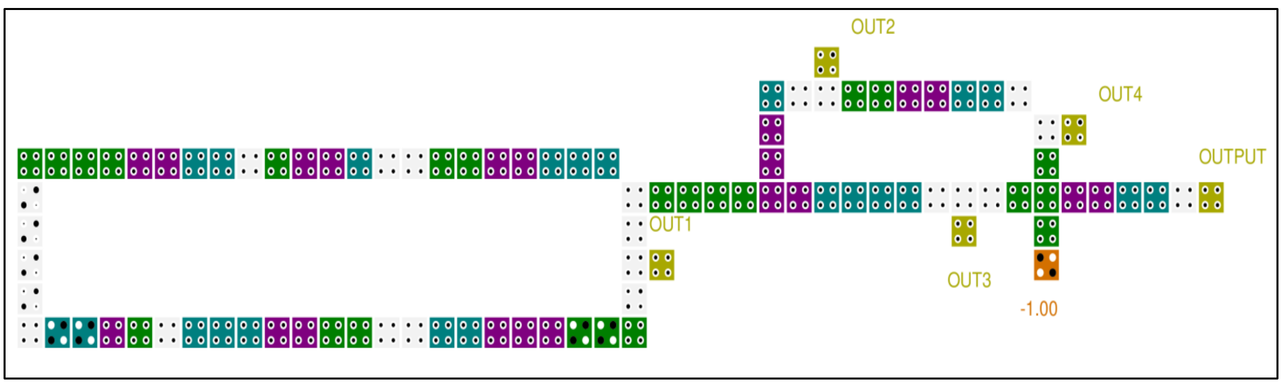


**Fig. 9**. The proposed circuit in QCADesigner.

## 4. RESULTS AND DISCUSSION

The results of circuit simulation with QCADesigner simulator are shown in Fig. 10. As the number of delay cells increases, the output pulse width increases, and the output frequency reduces. Using the QCADesigner simulator, the dimensions of the circuits can be obtained according to the number of cells, cells' dimensions, and their distances from each other, which is illustrated in Table 1. Accordingly, in the larger dimensions, the power consumption of the circuit increases slightly.

The functionality of the proposed circuit is based on an adjustable delay loop oscillator which generates the main signal. This signal is named OUT1 in Fig. 10. Other division values may be obtained by increasing or decreasing the delay value of the oscillator’s loop. Here and in this example, the delay value is 6 and the frequency will be divided by 12. After that the OUT2 and OUT3 signals will be derived by 1 clock delay from OUT1 signal.

Again 1 clock delay will take place on OUT2 signal, the result signal will be inverted (OUT4) and will pass through an AND gate with OUT3 signal. The output is named OUTPUT in Fig. 10. As mentioned before, this circuit is a divide by 12 frequency generator. It should be noticed that any other duty cycles are achievable by forcing more delay on OUT2 signal.

The unique feature of this circuit compared to similar circuits that have been designed and implemented in previous researches is the power consumption of this circuit, which is negligible and less than pico-watt. The power consumption in the QCA circuits is negligible because no current is established and the main function of the circuit is provided by the transfer of electrical charges within the cells. Moreover, the dimensions of the circuit are at the nanoscale, so that a length and width of about 20 nanometers is considered for each cell [17].

**Table 1.** Cell count, Area and Power consumption value for Frequency Dividers.

| Frequency Dividers | Cell Count | Area $(\mu m)^2$ | Power Consumption e-12w |
|---|---|---|---|
| 2 | 55 | 0.16 | 8.2 |
| 4 | 67 | 0.18 | 13.1 |
| 6 | 81 | 0.21 | 15.5 |
| 8 | 92 | 0.25 | 17.4 |
| 10 | 98 | 0.29 | 21.1 |
| 12 | 103 | 0.32 | 25.2 |
| 14 | 106 | 0.35 | 29.3 |

For better comparison, the consumed area and power consumption diagrams are shown in different frequencies in Fig. 11 and Fig. 12 respectively. Fig. 13 compares the cell counts of the circuits according to the output frequency.

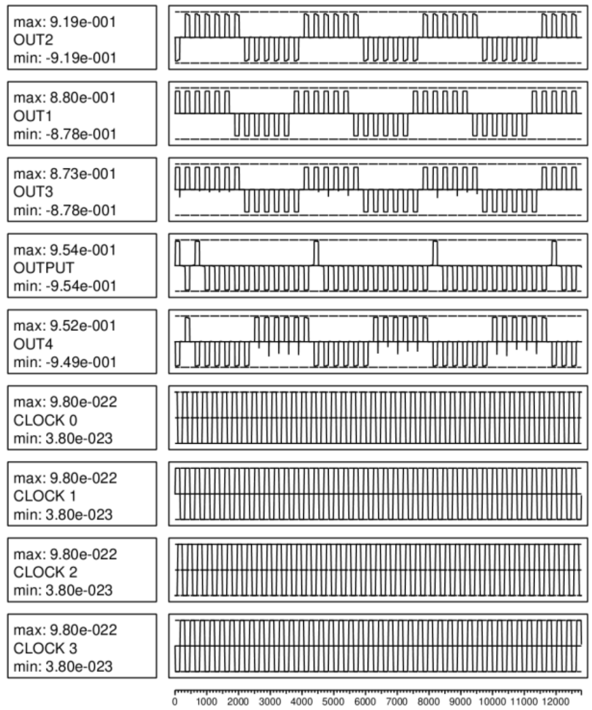


**Fig. 10.** The results of circuit simulation with QCADesigner.

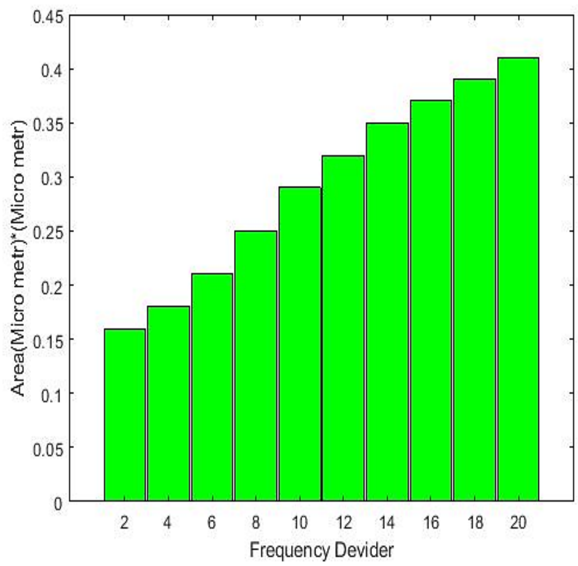


**Fig. 11**. Dimensions of different circuits according to the output frequency.

## 5. CONCLUSION

QCA is one of the emerging technologies that offer a new way of digital processing as a branch of nanotechnology. Since the dimensions and power consumption of the circuits implemented in this technology are very small, this technology can be used in designing circuits such as a pacemaker. In this paper, the pulse generator circuit in the pacemaker is designed and simulated by QCA cells and the main function of the circuit is confirmed in the QCAdesigner simulator. The variation of the output pulse width in this technology is easily possible by adding a delay cell. According to the small size of the circuit in square micrometer and low power consumption in pico-watts, it is suggested to use QCA technology in designing the pacemakers.

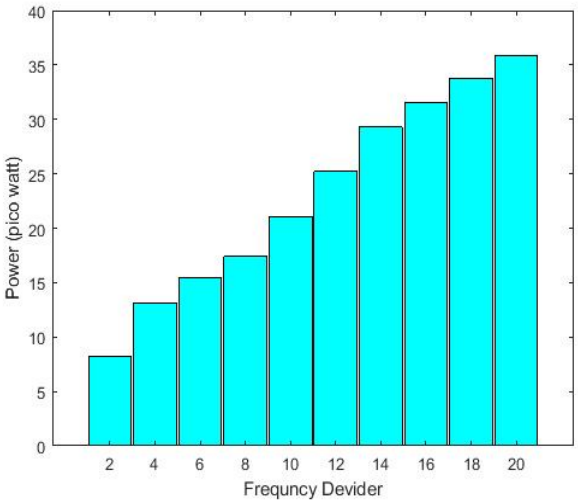


**Fig. 12**. The power consumption of the circuits according to the output frequency.

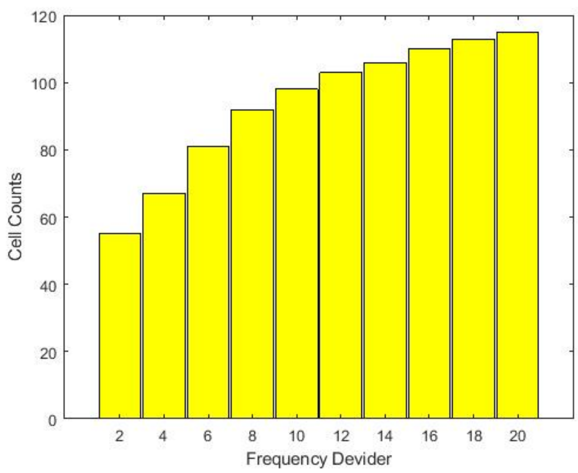


**Fig. 13**. The cell counts of the circuits according to the output frequency.

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