HE RF DC EMT
Harvesting Energy of Radio Frequency

By

HOSSAM MAHMOUD GAMAL ELDIN MOHAMMED ELANZEERY

FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
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CERTIFICATION OF APPROVAL

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Approved:

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UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

December 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Hossam Mahmoud Gamal ElDin Mohammed ElAnzeery

ABSTRACT

Renewable Energy sources are the center of attraction for research and development all over the world nowadays. Oil and Gas are no more the main source of Energy, consequently the demand of a lasting cheap source of energy that is environmental friendly, is the main challenge recently.

During the last decade, power consumption has decreased opening the field for energy harvesting to become a real time solution for providing different sources of electrical power.

Energy Harvesting is a new technology that is going to make a revolution in the coming decade. Energy Harvesting is a technique to provide alternative sources of energy that are environmental friendly and low in cost.

Radio Frequency Energy Harvesting is one of the methods to provide electrical energy from the ambient Radio Frequency Energy that already exists in the environment. For example Hand phones can be directly charged from Radio frequencies in the environment like 915 MHz. Laptops can be charged by frequencies like 2.45 GHz. RFID passive tags can be powered by these radio frequencies without the supply of any batteries increasing the range of passive RFID tags to longer distances with lower cost.

Radio Frequency Energy Harvesting can provide a world with batteryless devices. With RF Energy Harvesting, the true mobility can be achieved where mobile devices do not depend on centralized power sources for charging. Instead they make use of the existing energy in the environment.

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LIST OF ABBREVIATIONS

HE Harvesting Energy

RF Radio Frequency

DC Direct Current

EMT Electro Magnetic Theory

RFID Radio Frequency Identification

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Environment & Energy are two main topics that are the main concern nowadays all over the world. An alternative energy source that is environmental friendly could be a great solution to a lot of our environmental problems.

Within the past decade, wide range of wireless devices have been introduced that can provide efficient and practical solutions to consumer, industrial, and military needs. However, with existing technology, wireless devices are constrained by the amount of time they can be operated independent of centralized power sources. As a result, the usefulness of wireless devices, as well as the potential range of applications, is severely restricted by relatively slow advancements in rechargeable battery technology. As a result, a clear market need exists that either allows wireless devices to operate for longer durations away from centralized power sources or increases the amount of power that can be supplied to a wireless device. Currently, many technologies have been developed that attempt to overcome the limitations imposed on wireless devices. For example, recent advancements in rechargeable batteries and electric double-layer capacitors (i.e. supercapacitors), as well as technologies that harvest solar energy and exploit the piezoelectric effect have been effective at satisfying a large portion of the established market need.

Within the recent past, rechargeable battery capacity has been increasing by approximately 6% per year, and, as a result, the amount of time a wireless device can be used portably without being re-energized has improved. However, this only provides a partial solution to the inherent problem with powering wireless devices. Products that solely exploit improvements in battery life still present severe restrictions for applications that require long periods of independent operation away from centralized power sources.

Solar power technology has also developed into a viable solution for many industrial, commercial, and military applications. Nonetheless, at the current level of technology, solar power provides an inadequate solution for many wireless devices due to multiple seemingly insurmountable constraints. Some of these limitations include a solar cell's location relative to the sun, time of operation, and weather conditions, as well as the relatively high price per watt of power. Moreover, many wireless applications do not have access to sunlight due to their embedded location within structures.

Within the scientific community, much research has been devoted recently to developing piezoelectric energy harvesting devices. This technology exploits certain materials' ability to induce an electric potential after the application of a mechanical disturbance. For example, it is theoretically possible to design a device that can take advantage of applied pressure to a human kneecap during normal movement and use this mechanical motion to induce an electric potential. Many mechanical systems inherently create vibrational motion during operation, and consequently, this energy could be harvested.

Around 1891, the famous inventor and engineer Nikola Tesla proposed that radio frequency energy could be used to wirelessly power devices. Currently, passive radio frequency identification systems (such as RFID tags) are the only large scale implementation of the technology.

Powering embedded systems, and to some extent wireless sensor networks, requires significantly more power than a simple passive device like an RFID tag; however, in recent years, the technology has been researched for applications that require monitoring of a sensor network. In most of these applications, the location of the sensors (inside a rigid structure, for instance) does not allow for other forms of energy harvesting. Furthermore, providing sufficient wiring to the sensor network would be extremely costly and cumbersome.

Harvesting radio frequency energy has been discussed for monitoring the structural integrity of bridges, as well as overseeing environmental conditions within a sealed space (a nuclear reactor compartment, for instance). In most of these cases, the sensor network does not need to be run continuously, and, as a result, intentional power transmissions can be sent at specific times to power the devices.

1.2 Problem statement

The first major obstacle is that it is not a trivial problem to capture energy from the air. We will use a concept called energy harvesting. Energy harvesting is the idea of gathering transmitted energy and either using it to power a circuit or storing it for later use. Most people don't realize that there is an abundance of energy all around us at all times. We are being bombarded with energy waves every second of the day. The concept needs an efficient antenna along with a circuit capable of converting alternating-current (AC) voltage to direct-current (DC) voltage. The efficiency of an antenna, as being discussed here, is related to the shape and impedance of the antenna and the impedance of the circuit. If the two impedances aren't matched then there is reflection of the power back into the antenna meaning that the circuit was unable to receive all the available power. Matching of the impedances means that the impedance of the antenna is the complex conjugate of the impedance of the circuit. Another thing to think about is what would happen when you get away from major metropolitan areas. Since the energy we are trying to harness is being added to the atmosphere from devices that are present mostly in cities and are not as abundant in rural areas, there might not be enough energy for this technology to work. However, for the time being, we will focus on the problem of actually getting a circuit to work.

1.3 Objectives and scope of study

This thesis is considered to be one of the first steps towards what could become a standard circuit included in every cellular phone, and quite possibly every electronic device made. A way to charge the battery of an electric circuit without plugging it into the wall would change the way people use wireless systems. However, this technology needs to be proven first. It was decided to begin the project with a cellular phone because of the relative simplicity of the battery system.

Also, after we prove that the technology will work in the manner suggested, cellular phones would most likely be the first devices to have such circuitry implemented on a wide scale. This advancement coupled with a better overall wireless service can be expected to lead to the mainstream use of cell phones as people's only phones. This thesis is an empirical study of whether or not this idea is feasible. This first step is to get an external wireless circuit to work with an existing phone by transmitting energy to the phone (battery) through they air.

In order to prove the concept, power needs to be supplied to the energy harvesting circuit by an external transmitter. This transmitter will send a signal at the set frequency. Our test system will then receive this signal through the energy harvesting circuit. This circuit is the fundamental design problem of this thesis. This circuit will convert the received signal into DC voltage to charge the battery. The RF transmitter, the analysis of the cellular phones to be used, and the modification of cellular phone stands to accommodate the circuitry to be designed are elements of the research covered in this section. A set of experiments will be conducted to demonstrate the feasibility of this new technology.

CHAPTER 2
LITERATURE REVIEW

2.1 Energy harvesting

The use of Radio Frequencies (RF) for communication is considered a wireless related technology that already began a century ago. It is a milestone in modern life that has various types of applications. RF is one of a general class of energy carrying waves, which is defined in the electromagnetic spectrum.

RF signal is widely used nowadays specially in the communication field. Although thousands of radio waves propagate in the air, they do not interfere with each other because each RF transmission transmits at different frequency. Besides, certain range of frequency is specified according to the application.

Energy Harvesting can be defined as conversion of ambient energy present in the environment into electrical energy. RF radiation is used to power ID cards by directing high power electromagnetic energy to the devices from a nearby source. In addition to energy, it is possible to share information as well.

However, the term energy harvesting implies that the device gets its energy by making use of available energies in the surrounding environment. In cities and very populated areas there is a large number of potential RF sources: broadcast Radio and TV, mobile telephony, wireless networks, etc. The concept of RF Energy Harvesting is to collect all these disparate sources and convert them into useful energy. The conversion is based on a rectifying antenna (*rectenna*), constructed with a Schottky diode located between the antenna dipoles.

The energy levels actually present are so low that no present electronic device can use them. The goal of this project is to work on the fabrication of devices that would “recycle” RF energy generated for other purposes by different elements.

2.2 Wireless communication

Wireless communication is the transfer of information over a distance without the use of electrical conductors or "wires".

Wireless operations permits services, such as long range communications, that are impossible or impractical to implement with the use of wires. The term is commonly used in the telecommunications industry to refer to telecommunications systems (e.g., radio transmitters and receivers, remote controls, computer networks, network terminals, etc.) which use some form of energy (e.g. radio frequency (RF), infrared light, laser light, visible light, acoustic energy, etc.) to transfer information without the use of wires. Information is transferred in this manner over both short and long distances.

The term "wireless" has become a generic and all-encompassing word used to describe communications in which electromagnetic waves or RF (rather than some form of wire) carry a signal over part or the entire communication path.

The term "wireless" should not be confused with the term "cordless", which is generally used to refer to powered electrical or electronic devices that are able to operate from a portable power source (e.g. a battery pack) without any cable or cord to limit the mobility of the cordless device through a connection to the mains power supply. Some cordless devices, such as cordless telephones, are also wireless in the sense that information is transferred from the cordless telephone to the telephone's base unit via some type of wireless communications link. This has caused some disparity in the usage of the term "cordless", for example in Digital Enhanced Cordless Telecommunications. In the last fifty years, wireless communications industry experienced drastic changes driven by many technology innovations.

2.3 History of wireless communications

The term "Wireless" came into public use to refer to a radio receiver or transceiver (a dual purpose receiver and transmitter device), establishing its usage in the field of wireless telegraphy early on; now the term is used to describe modern wireless connections such as in cellular networks and wireless broadband Internet. It is also used in a general sense to refer to any type of operation that is implemented without the use of wires, such as "wireless remote control" or "wireless energy transfer", regardless of the specific technology (e.g. radio, infrared, ultrasonic) that is used to accomplish the operation.

2.4 Early wireless work

David E. Hughes, eight years before Hertz's experiments, induced electromagnetic waves in a signaling system. Hughes transmitted Morse code by an induction apparatus. In 1878, Hughes's induction transmission method utilized a "clockwork transmitter" to transmit signals. In 1885, T. A. Edison used a vibrator magnet for induction transmission. In 1888, Edison deploys a system of signaling on the Lehigh Valley Railroad. In 1891, Edison attains the wireless patent for this method using inductance.

In the *history of wireless technology*, the demonstration of the theory of electromagnetic waves by Heinrich Rudolf Hertz in 1888 was important. The theory of electromagnetic waves were predicted from the research of James Clerk Maxwell and Michael Faraday. Hertz demonstrated that electromagnetic waves could be transmitted and caused to travel through space at straight lines and that they were able to be received by an experimental apparatus. The experiments were not followed up by Hertz. The practical applications of the wireless communication and remote control technology were implemented by Nikola Tesla.

2.5 The electromagnetic spectrum

Light, colours, AM and FM radio, and electronic devices make use of the electromagnetic spectrum. In the US the frequencies that are available for use for communication are treated as a public resource and are regulated by the Federal Communications Commission. This determines which frequency ranges can be used for what purpose and by whom. In the absence of such control or alternative arrangements such as a privatized electromagnetic spectrum, chaos might result if, for example, airlines didn't have specific frequencies to work under and an amateur radio operator was interfering with the pilot's ability to land an airplane. Wireless communication spans the spectrum from 9 kHz to 300 GHz.

2.6 Applications of wireless technology

Security systems

Wireless technology may supplement or replace hard wired implementations in security systems for homes or office buildings.

Television remote control

Modern televisions use wireless (generally infrared) remote control units. Now radio waves are also used.

Cellular telephony (phones and modems)

Perhaps the best known example of wireless technology is the cellular telephone and modems. These instruments use radio waves to enable the operator to make phone calls from many locations world-wide. They can be used anywhere that there is a cellular telephone site to house the equipment that is required to transmit and receive the signal that is used to transfer both voice and data to and from these instruments.

2.7 Near field

These are wireless transmission techniques over distances comparable to, or a few times the diameter of the device(s).

2.8 Far Field

Far field methods achieve longer ranges, often multiple kilometer ranges, where the distance is much greater than the diameter of the device(s).

2.9 Induction

The action of an electrical transformer is the simplest instance of wireless energy transfer. The primary and secondary circuits of a transformer are not directly connected. The transfer of energy takes place by electromagnetic coupling through a process known as mutual induction. (An added benefit is the capability to step the primary voltage either up or down.) The battery charger of an electric toothbrush is an example of how this principle can be used. The main drawback to induction, however, is the short range. The receiver must be very close to the transmitter or induction unit in order to inductively couple with it.

2.10 Resonant induction

"Resonant inductive coupling" has key implications in solving the two main problems associated with non-resonant inductive coupling and electromagnetic radiation, one of which is caused by the other; distance and efficiency. Electromagnetic induction works on the principle of a primary coil generating a predominantly magnetic field and a secondary coil being within that field so a current is induced within its coils. This causes the relatively short range due to the amount of power required to produce an electromagnetic field. Over greater distances the non-resonant induction method is inefficient and wastes much of the transmitted energy just to increase range. This is where the resonance comes in and helps efficiency dramatically by "tunneling" the magnetic field to a receiver coil that resonates at the same frequency. Unlike the multiple-layer secondary of a non-resonant transformer, such receiving coils are single layer solenoids with closely spaced capacitor plates on each end, which in combination allow the coil to be tuned to the transmitter frequency thereby eliminating the wide energy wasting "wave problem" and allowing the energy used to focus in on a specific frequency increasing the range.

Beginning in the early 1960s resonant inductive wireless energy transfer was used successfully in implantable medical devices including such devices as pacemakers and artificial hearts. While the early systems used a resonant receiver coil later systems implemented resonant transmitter coils as well. These medical devices are designed for high efficiency using low power electronics while efficiently accommodating some misalignment and dynamic twisting of the coils. The separation between the coils in implantable applications is commonly less than 20 cm. Today resonant inductive energy transfer is regularly used for providing electric power in many commercially available medical implantable devices.

Wireless electric energy transfer for experimentally powering electric automobiles and buses is a higher power application (>10kW) of resonant inductive energy transfer. High power levels are required for rapid recharging and high energy transfer efficiency is required both for operational economy and to avoid negative environmental impact of the system. An experimental electrified roadway test track built circa 1990 achieved 80% energy efficiency while recharging the battery of a prototype bus at a specially equipped bus stop. The bus could be outfitted with a retractable receiving coil for greater coil clearance when moving. The gap between the transmit and receive coils was designed to be less than 10 cm when powered. In addition to buses the use of wireless transfer has been investigated for recharging electric automobiles in parking spots and garages as well.

Some of these wireless resonant inductive devices operate at low milliwatt power levels and are battery powered. Others operate at higher kilowatt power levels. Current implantable medical and road electrification device designs achieve more than 75% transfer efficiency at an operating distance between the transmit and receive coils of less than 10 cm.

In November 2006, Marin Soljačić and other researchers at the Massachusetts Institute of Technology applied the near field behaviour well known in electromagnetic theory to a wireless power transmission concept based on strongly-coupled resonators. In a theoretical analysis (see Ref: Annals of Physics), they demonstrate that, by designing electromagnetic resonators that suffer minimal loss due to radiation and absorption and have a near field with mid-range extent (namely a few times the resonator size), mid-range efficient wireless energy-transfer is possible. The reason is that, if two such resonant objects are brought in mid-range proximity, their near fields (consisting of so-called 'evanescent waves') couple (evanescent wave coupling) and can allow the energy to tunnel/transfer from one object to the other within times much shorter than all loss times, which were designed to be long, and thus with the maximum possible energy-transfer efficiency. Since the resonant wavelength is much larger than the resonators, the field can circumvent extraneous objects in the vicinity and thus this mid-range energy-transfer scheme does not require line-of-sight. By utilizing in particular the magnetic field to achieve the coupling, this method can be safe, since magnetic fields interact weakly with living organisms.

2.11 Radio and microwave

The earliest work in the area of wireless transmission via radio waves was performed by Heinrich Rudolf Hertz in 1888. A later Guglielmo Marconi worked with a modified form of Hertz's transmitter. Nikola Tesla also investigated radio transmission and reception.

Japanese researcher Hidetsugu Yagi also investigated wireless energy transmission using a directional array antenna that he designed. In February

1926, Yagi and Uda published their first paper on the tuned high-gain directional array now known as the Yagi antenna. While it did not prove to be particularly useful for power transmission, this beam antenna has been widely adopted throughout the broadcasting and wireless telecommunications industries due to its excellent performance characteristics.

Power transmission via radio waves can be made more directional, allowing longer distance power beaming, with shorter wavelengths of electromagnetic radiation, typically in the microwave range. A rectenna may be used to convert the microwave energy back into electricity. Rectenna conversion efficiencies exceeding 95% have been realized. Power beaming using microwaves has been proposed for the transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit has been considered.

Power beaming by microwaves has the difficulty that for most space applications the required aperture sizes are very large. For example, the 1978 NASA Study of solar power satellites required a 1-km diameter transmitting antenna, and a 10 km diameter receiving rectenna, for a microwave beam at 2.45 GHz. These sizes can be somewhat decreased by using shorter wavelengths, although short wavelengths may have difficulties with atmospheric absorption and beam blockage by rain or water droplets. Because of the Thinned array curse, it is not possible to make a narrower beam by combining the beams of several smaller satellites.

For earthbound applications a large area 10 km diameter receiving array allows large total power levels to be used while operating at the low power density suggested for human electromagnetic exposure safety. A human safe power density of 1 mW/cm^2 distributed across a 10 km diameter area corresponds to 750 megawatts total power level. This is the power level found in many modern electric power plants.

2.12 High power

Wireless Power Transmission (using microwaves) is well proven. Experiments in the tens of kilowatts have been performed at Goldstone in California in 1975 and more recently (1997) at Grand Bassin on Reunion Island. These methods achieve distances on the order of a kilometer.

2.13 Electrical conduction

Electrical energy can also be transmitted by means of electrical currents made to flow through naturally existing conductors, specifically the earth, lakes and oceans, and through the atmosphere — a natural medium that can be made conducting if the breakdown voltage is exceeded and the gas becomes ionized. For example, when a high voltage is applied across a neon tube the gas becomes ionized and a current passes between the two internal electrodes. In a practical wireless energy transmission system using this principle, a high-power ultraviolet beam might be used to form a vertical ionized channel in the air directly above the transmitter-receiver stations. The same concept is used in virtual lightning rods, the electrolaser electroshock weapon and has been proposed for disabling vehicles.

A "world system" for "the transmission of electrical energy without wires" that depends upon the electrical conductivity was proposed by Nikola Tesla as early as 1904. The *Tesla effect* is the application of a type of electrical conduction (that is, the movement of energy through space and matter; not just the production of voltage across a conductor).

Through longitudinal waves, an operator uses the Tesla effect in the wireless transfer of energy to a receiving device. The Tesla effect is a type of high field gradient between electrode plates for wireless energy transfer.

Wireless transmission of power and energy demonstration during his high frequency and potential lecture of 1891.The Tesla effect uses high frequency alternating current potential differences transmitted between two plates or nodes. The electrostatic forces through natural media across a conductor situated in the changing magnetic flux can transfer power to the conducting receiving device (such as Tesla's wireless bulbs).

Currently, the effect has been appropriated by some in the fringe scientific community as an effect which purportedly causes man-made earthquakes from electromagnetic standing waves, related to Tesla's telegeodynamics mechanical earth-resonance concepts. A number of modern writers have "reinterpreted" and expanded upon Tesla's original writings. In the process, they have sometimes invoked behavior and phenomena that are inconsistent with experimental observation. On the other hand, a number of researchers have experimented with Tesla's basic wireless energy transmission system design and made physical observations that are inconsistent with some basic tenets of mainstream science.

The Tesla world wireless system would combine electrical power transmission along with broadcasting and wireless telecommunications, allowing for the elimination of many existing high-tension power transmission lines and facilitate the interconnection of electrical generation plants on a global scale. However, a close reading of Tesla's patents suggests that he may have misinterpreted the 25-70 km nodal structures associated with lightning that he observed during his 1899 Colorado Springs experiments in terms of circumglobally propagating standing waves instead of as the well known local interference between direct and reflected waves between the ground and the ionosphere (not known to exist at the time). Many of the properties of the real earth-ionosphere cavity that have subsequently been mapped in great detail were unknown to Tesla, and a consideration of the earth-ionosphere waveguide propagation parameters as they are known today shows that Tesla's concept of a global wireless power grid is not practically realizable.

2.14 Radio-frequency identification (RFID)

Radio-frequency identification (**RFID**) is an automatic identification method, relying on storing and remotely retrieving data using devices called

RFID tags or transponders. The technology requires some extent of cooperation of an RFID reader and an RFID tag.

An RFID tag is an object that can be applied to or incorporated into a product, animal, or person for the purpose of identification and tracking using radio waves. Some tags can be read from several meters away and beyond the line of sight of the reader. Most RFID tags contain at least two parts. One is an integrated circuit for storing and processing information, modulating and demodulating a radio-frequency (RF) signal, and other specialized functions. The second is an antenna for receiving and transmitting the signal.

There are generally two types of RFID tags: active RFID tags, which contain a battery, and passive RFID tags, which have no battery.

Today, RFID is used in enterprise supply chain management to improve the efficiency of inventory tracking and management.

2.15 Energy harvesting techniques

Energy harvesting (also known as *Power harvesting* or *energy scavenging*) is the process by which energy is captured and stored. Frequently this term is applied when speaking about small autonomous devices, like those used in sensor networks. A variety of different sources exist for harvesting energy, such as solar power, thermal energy, wind energy, salinity gradients and kinetic energy.

Traditionally electrical power has been generated from fossil fuels in large, centralized plants. Large-scale ambient energy, such as sun, wind and tides, is widely available but trickier to harvest. In urban areas, there is a surprising amount of electromagnetic energy in the environment as a result of radio and television broadcasting.

Energy harvesting devices converting ambient energy into electrical energy have attracted much interest in both the military and commercial sectors. Some systems convert random motion, such as that of ocean waves, into electricity to be used by oceanographic monitoring sensors for autonomous operation. Future applications may include high power output devices (or arrays of such devices) deployed at remote locations to serve as reliable power stations for large systems. All of these devices must be sufficiently robust to endure long-term exposure to hostile environments and have a broad range of dynamic sensitivity to exploit the entire spectrum of wave motions.

Energy can also be harvested to power small autonomous sensors such as those developed using MEMS technology. These systems are often very small and require little power, but their applications are limited by the reliance on battery power. Scavenging energy from ambient vibrations, wind, heat or light could enable smart sensors to be functional indefinitely.

Typical power densities available from energy harvesting devices are highly dependent upon the specific application and design of the harvesting generator. For motion powered devices, typical values are a few μW/cc for human body powered applications and hundreds of μW/cc for generators powered from machinery

2.16 Motivation

The history of energy harvesting dates back to the windmill and the waterwheel. People have searched for ways to store the energy from heat and vibrations for many decades. One driving force behind the search for new energy harvesting devices is the desire to power sensor networks and mobile devices without batteries. Energy harvesting is also motivated by a desire to address the issue of climate change and global warming.

2.17 Devices

There are many small-scale energy sources that generally cannot be scaled up to industrial size:

1. Piezoelectric crystals or fibers generate a small voltage whenever they are mechanically deformed. Vibration from engines can stimulate piezoelectric materials, as can the heel of shoe
2. Some wristwatches are already powered by kinetic energy, in this case movement of the arm. The arm movement causes the magnet in the electromagnetic generator to move. The motion provides a rate of change of flux, which results in some induced emf on the coils. The concept is simply related to Faraday's Law.
3. Thermoelectric generators produce energy from the heat difference between two objects. This is also used to power a wristwatch, as heat energy from the human body is radiated through the watch into the environment. Other than powering wristwatch, thermoelectric generators are also promising in the low power applications like wireless body area network (WBAN). Human, as an heat energy source, provides the electrical power to sustain the operation of the sensing and communicating devices. The operation is expected to last until the hardware fails.
4. Micro wind turbine are used to harvest wind energy readily available in the environment in the form of kinetic energy to power the low power electronic devices such as wireless sensor nodes. When air flows across the blades of the turbine, a net pressure difference is developed between the wind speeds above and below the blades. This will result in a lift force generated which in turn rotate the blades. This is known as the aerodynamic effect.
5. Special antennae can collect energy from stray radio waves or theoretically even light (EM radiation).

2.18 Ambient-radiation sources

A possible source of energy comes from ubiquitous radio transmitters. Unfortunately, either a large collection area or close proximity to the radiating source is needed to get useful power levels from this source.

One idea is to deliberately broadcast RF energy to power remote devices: This is now commonplace in passive Radio Frequency Identification (RFID) systems, but the Safety and US Federal Communications Commission (and equivalent bodies worldwide) limit the maximum power that can be transmitted this way.

2.19 Piezoelectric energy harvesting

The piezoelectric effect converts mechanical strain into electrical current or voltage. This strain can come from many different sources. Human motion, low-frequency seismic vibrations, and acoustic noise are everyday examples. Except in rare instances the piezoelectric effect operates in AC requiring time-varying inputs at mechanical resonance to be efficient.

Most piezoelectric electricity sources produce power on the order of milliwatts, too small for system application, but enough for hand-held devices. One proposal is that they are used for micro-scale devices, such as in a device harvesting micro-hydraulic energy. In this device, the flow of pressurized hydraulic fluid drives a reciprocating piston supported by three piezoelectric elements which convert the pressure fluctuations into an alternating current.

Piezoelectric systems can convert motion from the human body into electrical power. DARPA has funded efforts to harness energy from leg and arm motion, shoe impacts, and blood pressure for low level power to implantable or wearable sensors. Careful design is needed to minimise user discomfort. These energy harvesting sources by association have an impact on the body. An international Workshop is organized by Virginia Tech on Piezoelectric Energy Harvesting every year which reviews the past developments and current state of the technology .

The use of piezoelectric materials to harvest power has already become popular. Piezoelectric materials have the ability to transform mechanical strain energy into electrical charge. Piezo elements are being embedded in walkways to recover the "people energy" of footsteps. They can also be embedded in shoes to recover "walking energy".

2.20 Pyroelectric energy harvesting

The pyroelectric effect converts a temperature change into electrical current or voltage. It is analogous to the piezoelectric effect, which is another type of ferroelectric behavior. Like piezoelectricity, pyroelectricity requires time-varying inputs and suffers from small power outputs in energy harvesting applications. One key advantage of pyroelectrics over thermoelectrics is that many pyroelectric materials are stable up to 1200 C or more, enabling energy harvesting from high temperature sources and thus increasing thermodynamic efficiency. There is a pyroelectric scavenging device that was recently introduced, however, that doesn't require time-varying inputs. The energy-harvesting device uses the edge-depolarizing electric field of a heated pyroelectric to convert heat energy into mechanical energy instead of drawing electric current off two plates attached to the crystal-faces. Moreover, stages of the novel pyroelectric heat engine can be cascaded in order to improve the Carnot efficiency.

2.21 Thermoelectrics

In 1821, Thomas Johann Seebeck discovered that a thermal gradient formed between two dissimilar conductors produces a voltage. At the heart of the thermoelectric effect is the fact that a temperature gradient in a conducting material results in heat flow; this results in the diffusion of charge carriers. The flow of charge carriers to the low-temperature region in turn creates a voltage difference. In 1834, Jean Charles Athanase Peltier discovered that running an electric current through the junction of two dissimilar conductors could, depending on the direction of current flow, act as a heater or coolant. The heat absorbed or produced is proportional to the current, and the proportionality constant is known as the Peltier coefficient. Today, due to knowledge of the Seebeck and Peltier effects, thermocouples exist as both heaters and coolers.

Ideal thermoelectric materials have a high Seebeck coefficient, high electrical conductivity, and low thermal conductivity. Low thermal conductivity is necessary to maintain a high thermal gradient at the junction. Standard thermoelectric modules manufactured today consist of P- and N-doped bismuth-telluride semiconductors sandwiched between two metallized ceramic plates. The ceramic plates add rigidity and electrical insulation to the system. The semiconductors are connected electrically in series and thermally in parallel.

2.22 Electrostatic (capacitive) energy harvesting

This type of harvesting is based on the changing capacitance of vibration-dependent varactors. Vibrations separate the plates of an initially charged varactor (variable capacitor), and mechanical energy is converted into electrical energy.

2.23 Future Directions

Electroactive polymers (EAPs) have been proposed for harvesting energy. These polymers have a large strain, elastic energy density, and high energy conversion efficiency. The total weight of systems based on EAPs is proposed to be significantly lower than those based on piezoelectric materials.

CHAPTER 3
METHODOLOGY

3.1 Tools and equipment

This project is a combination of hardware and software as well but it is mainly concerned on the hardware part where the software's are just used to test and predict better performance for these hardware components.

For the software part:

- Simulation software's like PSPICE and Simulink are used.
- ADS (Advanced Design System)
- AWR Microwave office
- HFSS (High Frequency Structure Simulator)
- MATLAB

Moreover, for the hardware part:

- Electronic components such as capacitors, diodes, antennas and transceiver circuits.

3.2 Project procedures

As stated before, the project went through different stages in order to achieve the objective. The following chart illustrates these stages:

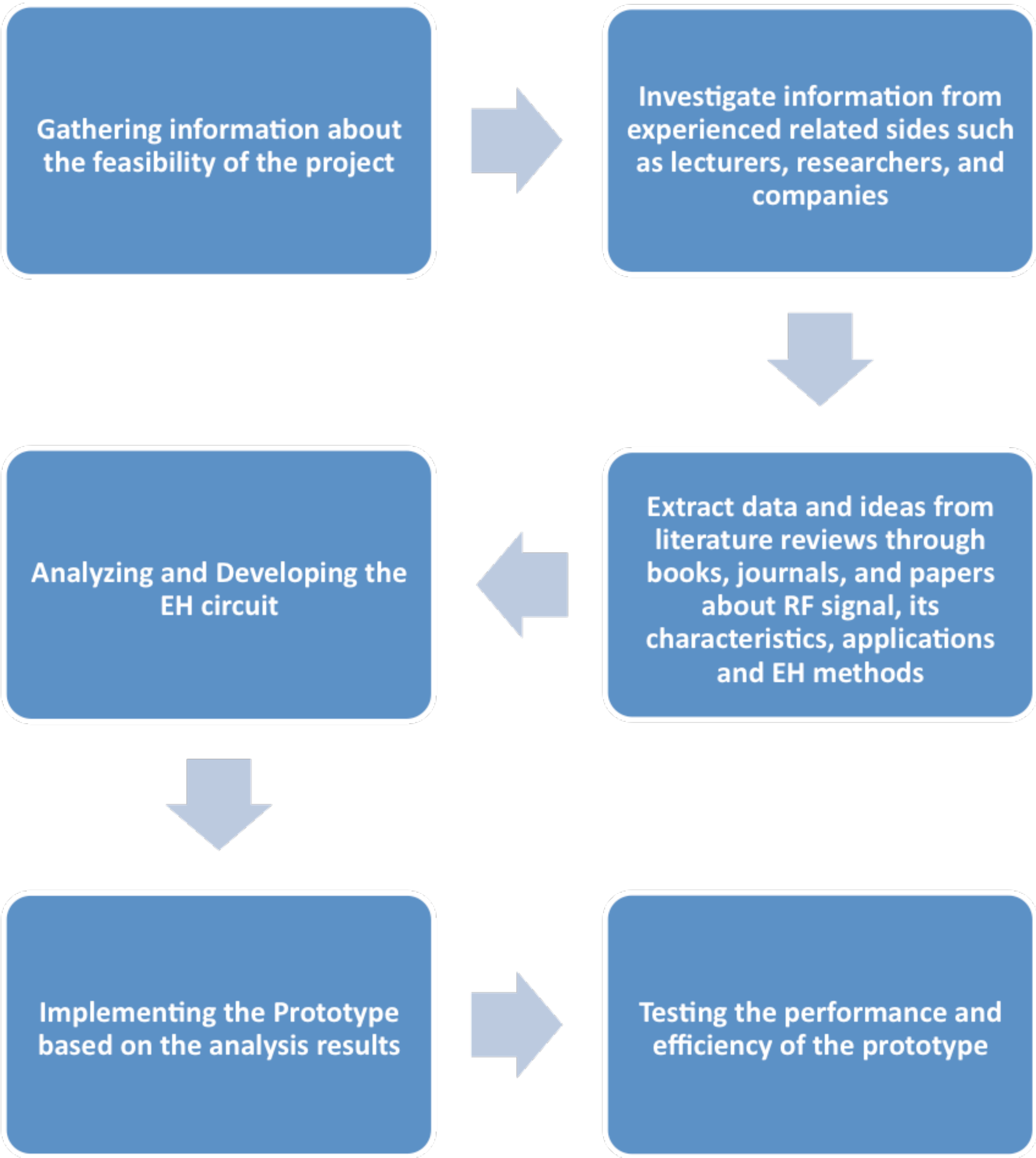

Figure 1: Flow chart of the project

3.3 Technical procedures

- The project is started by studying the technology of Energy Harvesting as a challenging new technology for the coming Future.
- Different Types of Energy Harvesting have been studied and observed including Solar, Piezoelectric, Pyroelectric, thermal and Radio Frequency Energy Harvesting.
- Radio Frequency Energy Harvesting was briefly studied despite of the limited resources available for this new technology.
- A basic circuit has been developed in this early stage to have better practical understanding about this technology and circuit components.
- This basic model was developed using frequencies of 315 MHz and 430 MHz.
- Another circuit model was developed based on try and error due to the unavailability of High Frequency Simulation Software but it does not work efficiently.
- Multisim, Advanced Design Simulation Software and Microwave office have been used to simulate a new effective circuit based on further studies and experience gained from previous model.
- Very good results were obtained for a frequency of 915 MHz while other models did not give convenient results for different frequencies.
- Researches have been done with trials of different models of circuitry for wide ranges of frequencies.
- Excellent simulation results were obtained with the final model circuitry.
- A brief studies and researches were implemented to provide a complete reference for the best possible circuit models available for each frequency of a range of specified frequencies.
- A prototype is still pending some circuit components that were ordered online and yet not received.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Overview of system design

The RF energy-harvesting device consists of three primary subsystems. The first subsystem is the receiving antenna, which is solely responsible for capturing all of the RF energy that will later be used to power the integrated embedded system. The second main subsystem is the rectification circuitry, which will efficiently convert the time varying input energy into a constant output voltage. The third subsystem is the energy storage system, which is responsible for storing all captured energy and providing a constant output voltage to power the attached device. Each one of these three subsystems is integral to the operation of the entire system.

4.2 RF harvesting subsystems

The major design specifications for each subsystem are listed below. These specifications were decided after a large number of experiments that involved different types of antennas, diodes and capacitors. Finally, it was decided to use 3.25 GHz, which falls within the S-band frequency, due to its high stability and output efficiency.

Table 1: Antenna Specifications

Resonant Frequency	3.25 GHz
Bandwidth	> 3000 KHz
Antenna Gain	6 dBi
Polarization	Linear
Radiation Pattern	3 dB Directivity
Effective area	4.12 * 10^-3 m2

Table 2: Rectification circuit specification

Input Frequency	3.25 GHz
Output Frequency	0 Hz (DC Signal)
Input Voltage Range	0.5 V – 3.68 V
Output Voltage	3.3 V
Power Efficiency	>80%

The S-Band RF energy-harvesting device consists of three subsystems. The first primary subsystem is the receiving antenna, which is solely responsible for capturing all of the RF energy that is used to power the integrated embedded system. The second primary subsystem is the rectification circuitry, which will efficiently convert the time varying input energy into a constant output voltage. The third subsystem is the energy storage and distribution system, which is responsible for acting as a power backup by storing captured energy in super capacitors. The overall device can operate effectively without the third subsystem, although some flexibility is lost in its operation. Therefore, this project will focus on the first two primary subsystems.

4.3 Receiving antenna subsystem

The antenna subsystem for the RF harvesting project was planned to be designed with an array of micro-strip receiving antennas printed onto an integrated circuit board. These receiving antennas will be placed on one side of the board with the rectification and storage subsystem placed on the other side. Operating within the specified frequency band this antenna array is tuned to receive maximum power at that frequency. The design will consist of multiple antennas connected in series or a microstrip antenna in order to maximize the total energy harvested by the antenna array. Specific antenna array layout is contingent upon final size dimensions of the rectification and energy storage subsystems, but will consist of multiple loops of micro-strip traces designed with a specific technique to save space as well as tune the antenna to the correct operating frequency.

4.4 Design approach

When designing an antenna there are certain trade-offs between antenna size and antenna performance. It is possible to select a large antenna that could collect a large amount of RF energy and higher efficiency; however, this would hinder many applications where a small antenna is crucial. Many different antenna designs would work for RF energy harvesting, but as electronic components become smaller and smaller through the progression of technology the need for smaller and smaller efficient antennas becomes more prevalent every day. Using a small micro-strip antenna array printed onto possibly a PCB will allow for the most versatility with various applications and add to the functionality of the device.

Micro-strip antennas are essentially made up of continuous metal layer patterns printed onto printed circuit boards. Many different micro-strip patterns can be used, including square, rectangular, or circular. Micro-strip antennas are very inexpensive, lightweight, and easily manufactured consisting of only a specific pattern etched into a metal trace bonded to an insulating dielectric substrate. However, micro-strip antennas are subject to radiation losses due to their surface wave properties and wave- trapping effects. These losses only increase with higher operating frequencies.

An important part of antenna design is achieving resonance at the designed operating frequency, which must be done by matching the impedance of the rectification circuit with the antenna. This will help to limit these radiation losses. Additionally, they have somewhat of a lower efficiency, in the range of 40-70%, than other flat-profile antenna types. Micro-strip antennas have many advantages over other antenna types. The ability for micro-strip antennas to conform to any surface, including walls, missiles, vehicles, etc, presents a nearly endless amount of applications.

Table 3: Microstrip Antenna characteristics

Advantages	Disadvantages
Lightweight	Narrow Bandwidth
Low profile (Aerodynamic)	Limited Maximum Gain
Easy to design and construct	Poor Directivity
Inexpensive to fabricate	Susceptible to high losses
Easily Integrated with existing electronics	Low power handling
Multiple Resonating Frequencies possible	Only practical at higher frequencies
Matching Network/Feed line fabricated with Antenna	Poor antenna-feed isolation

4.5 Technical description

The microstrip patch antenna was constructed using Rogers Corporation RT/duroid© 5880 High Frequency Laminate. RT duroid is a commonly selected material for microstrip and stripline circuit applications. More importantly, this specific laminate has an extremely low loss tangent, and has a constant dielectric constant over a wide range of high frequencies. A layer of electrodeposited copper cladding comes standard on both sides of the laminate. A summary of the relevant specifications of Rogers Corporation RT/duroid© 5880 can be found in the Table below.

Table 4: Microstrip Antenna Substrate Specifications

Dielectric constant	2.20 +/- 0.02 spec.
Loss tangent	0.0009
Height of dielectric substrate	3.175 mm
Copper cladding	1 oz. (35 um)

Using ADS (Advanced Design System), Matlab and a set of universal equations describing the properties of microstrip patch antennas, the critical properties of the designed antenna were theoretically calculated.

Table 5: Overview of theoretical Antenna Specifications

Microstrip Patch Antenna Width	36.49 mm
Microstrip Patch Antenna Length	27.75 mm
Ground Plane Width	36.51 mm
Ground Plane Length	27.77 mm
Antenna Input Impedance	100 ohm
Antenna Gain	6.0 dBi
Polarization	Linear

Based on the theoretical calculations for the microstrip patch antenna, the input characteristics to the rectification subsystem were determined, and these values are summarized in the table below. These calculations rely upon the assumption that the designed antenna will have a minimum bandwidth of 3000 kHz, this ensures the integrity of the input power calculations that much of the design is based on. Although microstrip patch antennas typically suffer from a narrow bandwidth, a simple patch design will yield a bandwidth of approximately 1% to 5% of the resonant frequency. For an antenna designed to operate at 3.25 GHz, this results in a bandwidth of 32.5 MHz to 162.5 MHz, which is many order of magnitudes greater than the minimum required bandwidth.

Table 6: Theoretical rated input characteristics to rectification circuitry

Input power to rectification circuitry	135.2 mW
Input voltage to rectification circuitry	3.68 V
Input current to rectification circuitry	36.74 mA

Moreover, these calculations assume a constant power density, which will obviously not be the case while harvesting from ambient sources. However, these calculated input characteristics provide a baseline that can be used to compare actual measured values against. These calculations also do not take into account losses that will undoubtedly be observed in the microstrip transmission line and radiating element. Nonetheless, these input characteristics are much greater than the minimum specifications needed to successfully power low-power devices.

4.6 Rectification subsystem

The rectification subsystem will take the output from the antenna in the form of a sine wave and convert it to a steady direct current voltage. This circuit will also increase the output voltage to a level that will be usable by the supercapacitor charger. A simple approach is to use diodes in a half or full bridge rectifier circuit. The problem with this approach for this application is that normal diodes have a turn-on voltage, Vth, of 0.7 V. This large turn-on voltage will consume most of the power that is harvested by the antenna and greatly reduce the operational efficiency of the system. To avoid this problem, Germanium diodes were used in the beginning that have a Vth of 0.3 V but it did not succeed. In this preliminary design, charge pumps will be used to rectify the AC input and multiply the voltage before delivering it to the supercapacitor charger as a nearly pure DC voltage.

Charge pumps work in stages that progressively increase the output voltage in a DC form. By increasing the number of stages of the charge pump it is theoretically possible to deliver any needed output voltage. The only constraint is that the circuit must obey Ohm's law. In other words, by increasing voltage, current is sacrificed.

The concept of the doubler circuit can be expanded into "n" stages by cascading charge pumps until the desired output voltage is reached. However, when this circuit is applied to a load, that load will drain charge from the capacitors and decrease the output voltage. The output voltage depends on the load placed on the circuit and the current load must be taken into account when computing what the output voltage will be.

4.7 Technical description

The rectification system can be self-fabricated onto a printed circuit board that also includes the microstrip patch antenna. A Faraday cage separates the antenna from the rectification circuitry, ensuring that neither subsystem electrically interferes with the other.

All components needed for the rectification circuitry come in a through hole mount package. Through hole components are easier to use than surface mount. Surface mount components were originally going to be used, but the idea was abandoned due to technical difficulties in the construction phase.

To determine the values for the capacitors, many variables were taken into effect. The major variable was the amount of energy that was to be harvested by the antenna system, then the requirements for the energy storage system. For these calculations, a value of 500 mV output from the antenna was assumed.

The system was designed to deliver 3 V and 3 mA to the energy storage system. These values were determined by evaluating the other systems. Knowing that the antenna will provide 500 mV at 36.74 mA, it was determined that the rectification system should be designed to deliver 3 V. This is 0.2 V above the minimum. This value was decided on to take into account any losses and to give a slight buffer if the antenna does not deliver exactly 500 mV. The 36.74 mV input current was then halved to give a worst case scenario for losses. Then using Ohm's law, it was determined that 3.03 mA would be delivered to the energy storage system. In addition to that, it was determined that the capacitance must be 34.6 pF.

However, after simulating the circuit, it was decided that the capacitor values were too small. As a result, 560 pF capacitors were used. Next, diodes had to be found that would work in the S-Band. The problem with such high frequencies is that the time that a standard diode takes to transition from its forward to reverse bias state is longer that one period at 3.25 GHz. Therefore, diodes with a very fast switching time had to be used. Also, since this project operates at very low voltage levels, Schottky diodes were used. Schottky diodes use a metal-semiconductor junction instead of a semiconductor-semiconductor junction. This allows the junction to operate much faster and gives a forward voltage drop of 0.15 - 0.45 V instead of 0.7 - 1.7 V of normal diodes. The specifications for the specific parts that were used in the final design can be found in the tables below.

Table 7: Design Specifications for the capacitors

Manufacturer	Prosperity Dielectric
Part number	MA0603XR-561K-500PR
Capacitance	560pF
Rated voltage	50 VDC
Mounting	Through Hole
Temperature Tolerance	X7R

Table 8: Design Specifications for the Schottky diodes

Manufacturer	Avago Technologies
Part number	5082-2835
Forward Voltage	0.34 V
Maximum Frequency	12 GHz

At this point, the output of the system is determined by the input received from the antenna. All of the calculations were done assuming minimum power values. But the antenna has the ability to deliver up to 3.6 V. If this happens, the output of the rectification system will be nearly 16 V.

4.8 Energy storage subsystem

The energy storage subsystem is responsible for storing all harvested radio frequency energy after rectification. It must also provide a constant output voltage and current to power an LED (or embedded systems). The exact capacitance of the series supercapacitors has not been determined.

Supercapacitors are electrochemical capacitors that provide thousands of times the storage capacity of a typical capacitor. Although the technology has been around for many years, in recent years supercapacitor technology has provided much higher energy densities in a much smaller package, allowing for inclusion in a wider array of applications. Unfortunately, the energy densities of supercapacitors are still typically only one-fifth to one-tenth that of rechargeable batteries. However, there is no risk of overcharging a supercapacitor, and they can be fully charged in seconds. Supercapacitors can also be charged and discharged millions of times before needing to be replaced, making them an ideal choice for applications where access to the energy storage component is extremely costly and time consuming.

4.9 Industry

In order to be updated with the latest technology and support, companies related to energy harvesting and RFID are contacted like Ecosensa, Consurv, Infineon and other communication companies. Internationally, the first conference in the world related to Energy Harvesting was conducted in June 2009 in Cambridge University in UK, but it was concerned on available new technologies for energy harvesting like solar, wind and energy from piezoelectric devices. However, RF energy harvesting is not yet reliable to be discussed in an international conference, as the researches in this field are still new.

4.10 Components used in early stages

- In order to have a stable signal, a transmitter is bought for 433 MHz.
- A receiver circuit is obtained as well to ensure the stability of the transmitter. Moreover, different capacitor values like 33uF, 33nF, 47uF, and47nF were tested in the receiver circuit to choose the one with best performance.
- In addition to that, two main types of diodes were used which are Germanium and Schottky diodes to compare the results on both of them.
- It was found that Germanium diode has the ability to rectify the RF ambient energy but with a very low output voltage, however Schottky diodes were found to provide higher voltage but their efficiency to rectify the RF energy is very low.
- Monopole Antenna is implemented in the receiver circuit and the whole receiver circuit was simulated by PSPICE.

4.11 Selected Frequencies

Basically, the idea of this project came up in order to serve RFID as an application to this new technology. The idea was to increase the range of RFID passive tags by making it able to harvest RF energy from the environment and convert it to electric energy.

Consequently, a decision has to be done on which frequency to be used. At the beginning, it was decided to use 915 MHz to widen the applications to include hand phones as well. However, we did not reach a good circuitry model at this time. Then, 1.3 GHz went instead due to its ability of supplying higher power. A convenient circuit model was built to generate 1.5 V, which can be used to supply another circuit that uses a 1.5 V battery to convert to 3.6 V.

However, the objective of the project has changed to be a complete study for this new challenging technology. Moreover, it has aimed to provide a pure electric current without any use of batteries, but instead to be able to replace all kind of batteries and wires and make this technology effective for different wide applications.

At this point, the project turned to have a different point of view. Another circuitry model has been developed that can cope with the changes that have been done. This new model has the ability to overcome all the defects of the previous model. In addition to that, it has eliminated completely the use of batteries.

As the objective of the project has changed, it was necessary to observe the effect of the new model on different frequencies and the results were astonishing. The frequencies that have been selected are: 50MHz, 315 MHz, 430 MHz, 500 MHz, 915 MHz, 1.3 GHz and 9 GHz.

4.12 Simulation Results

A brief study has been developed for a large range of frequencies including 50MHz, 315 MHz, 430 MHz, 500 MHz, 915 MHz, 1.3 GHz and 9 GHz as shown below:

For 3-stage circuit:

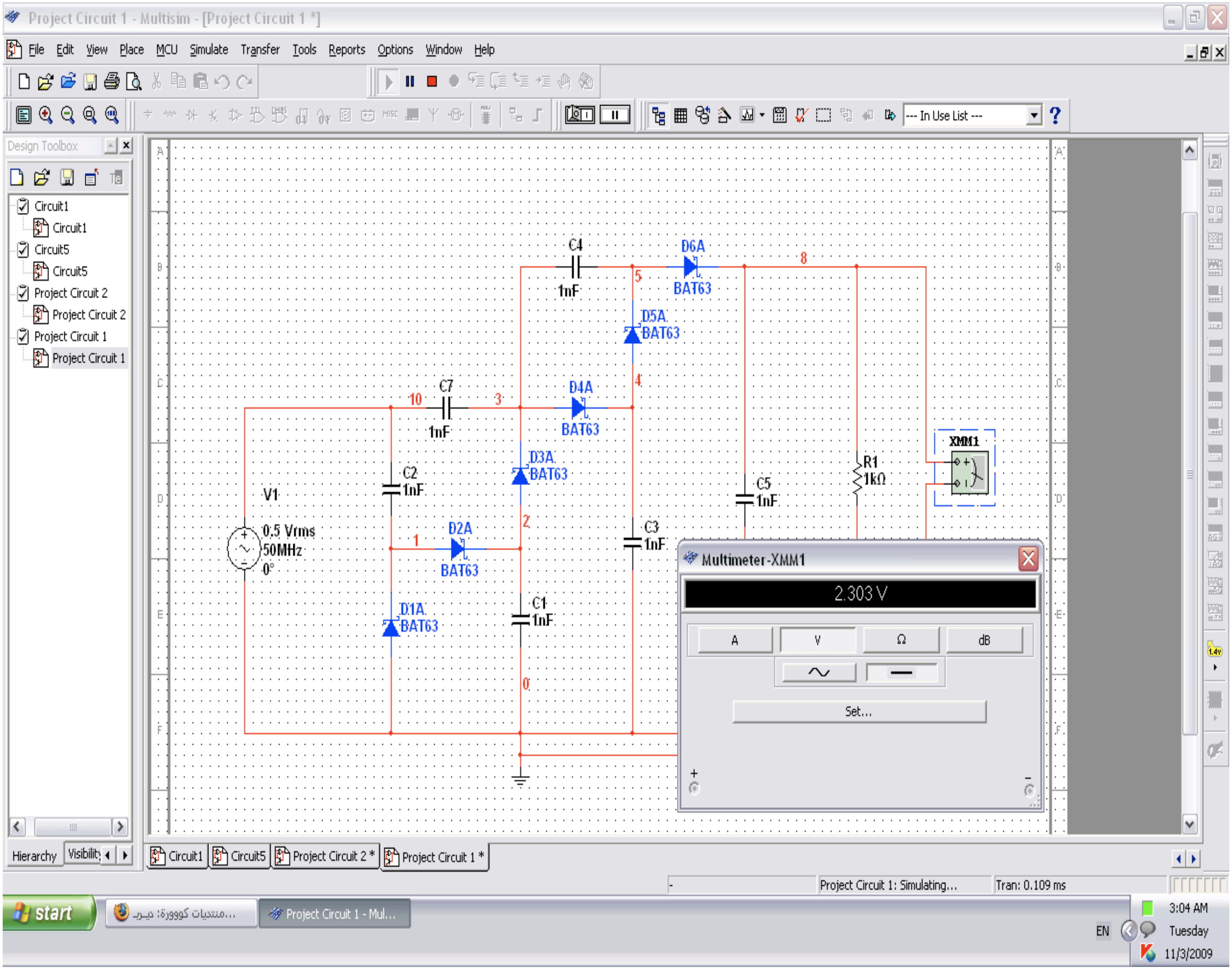

Figure 2: 50 MHz with 2.303 V

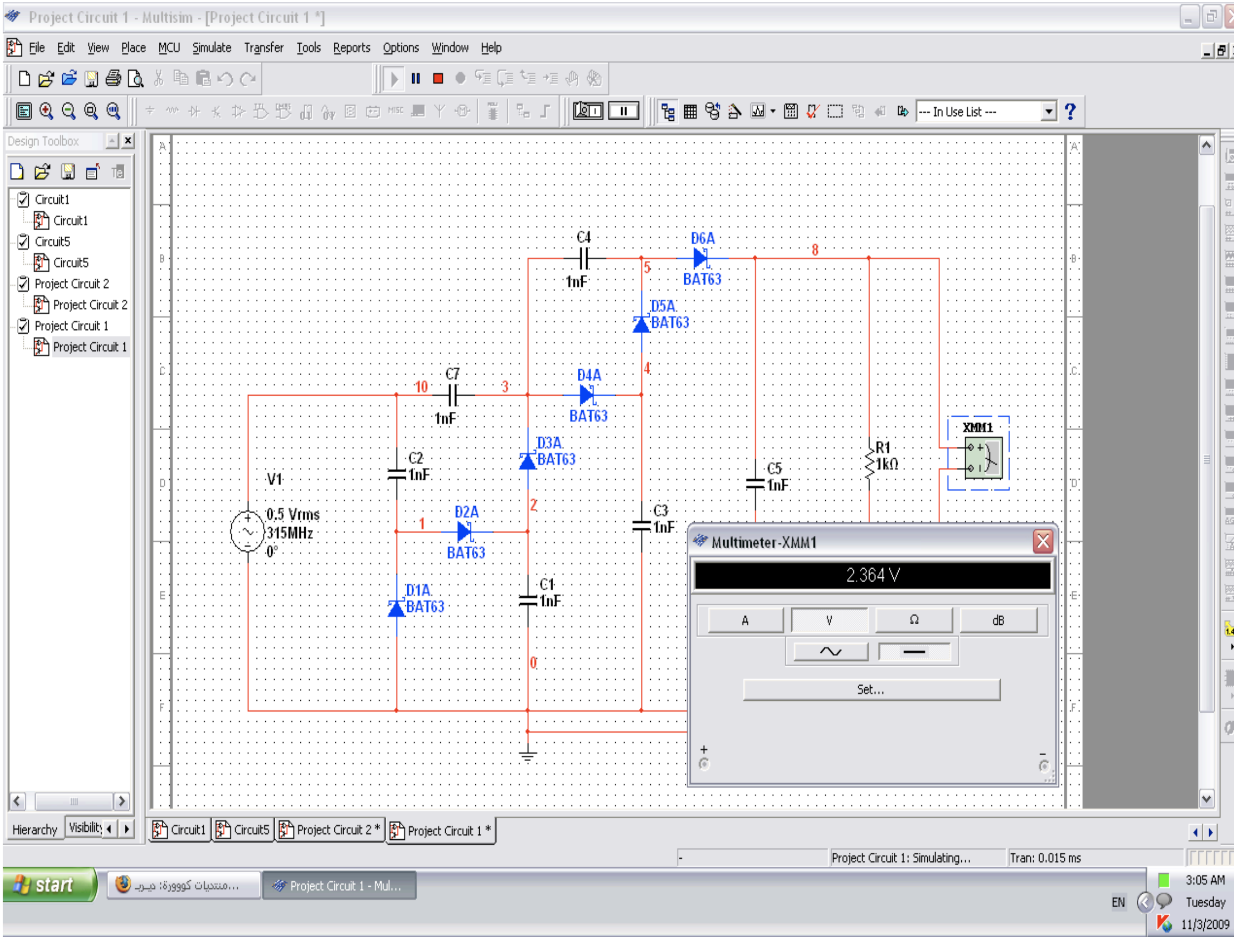

Figure 3: 315 MHz with 2.364 V

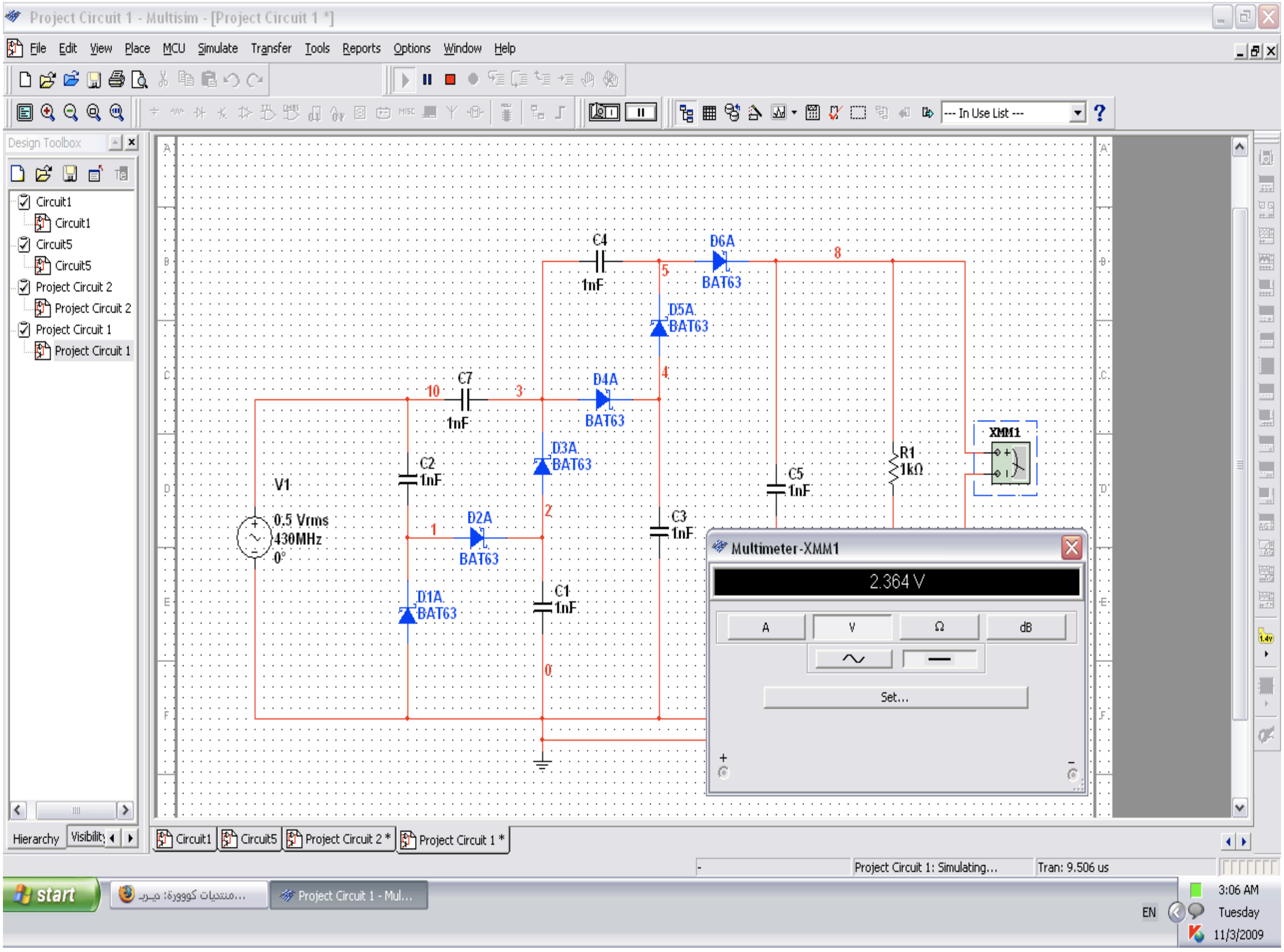

Figure 4: 430 MHz with 2.364 V

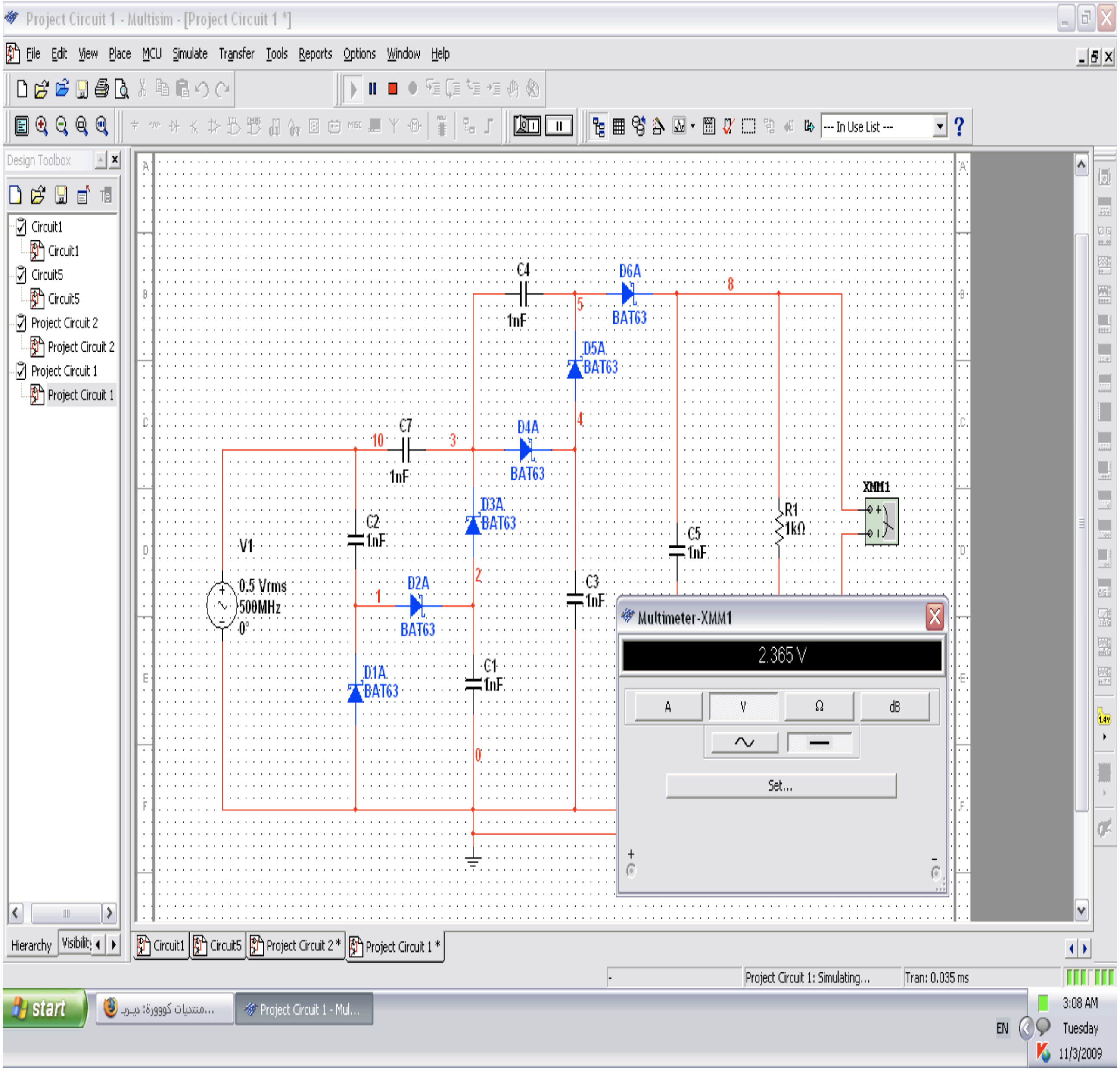

Figure 5: 500 MHz with 2.365 V

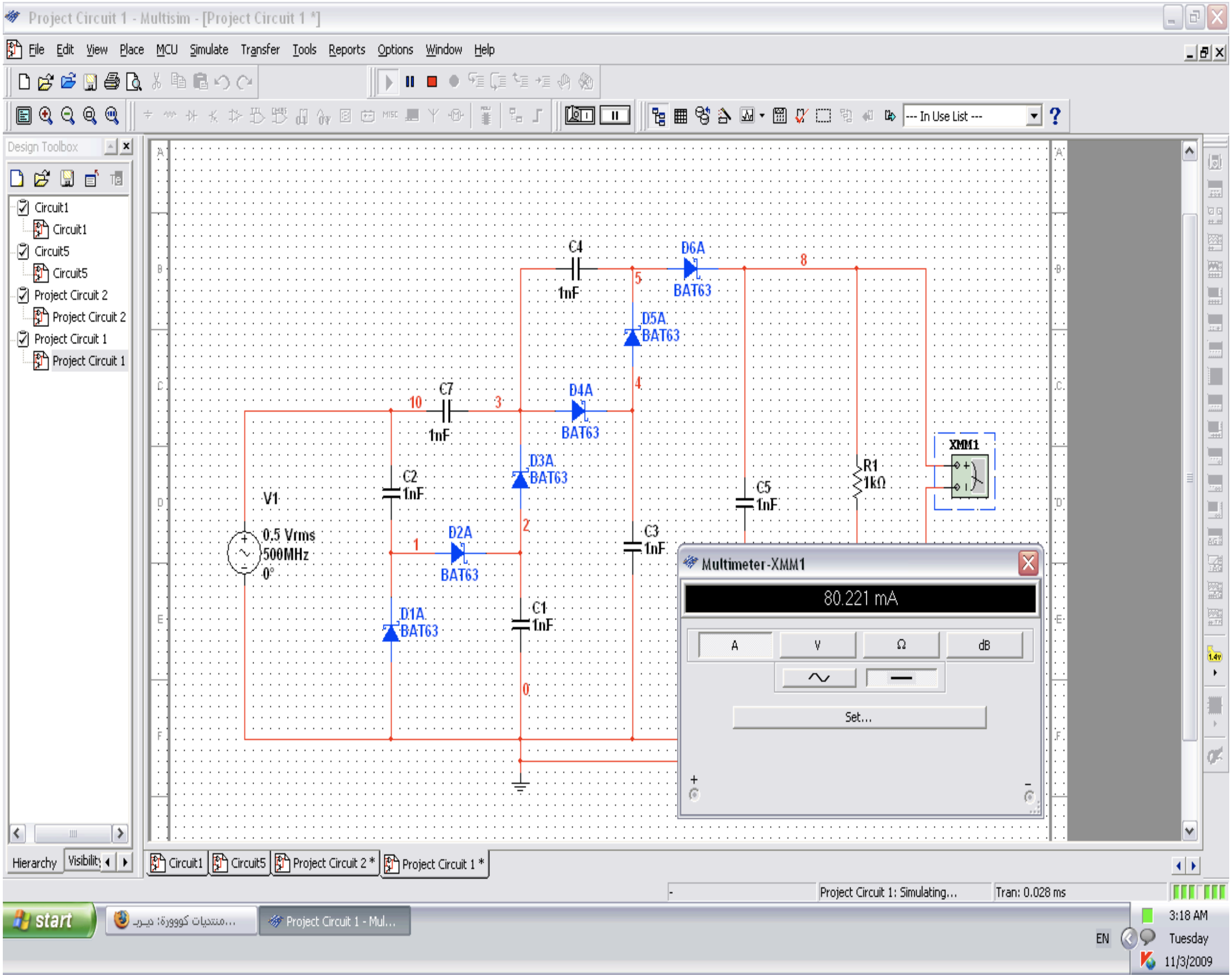

Figure 6: 500 MHz with 80.221 mA

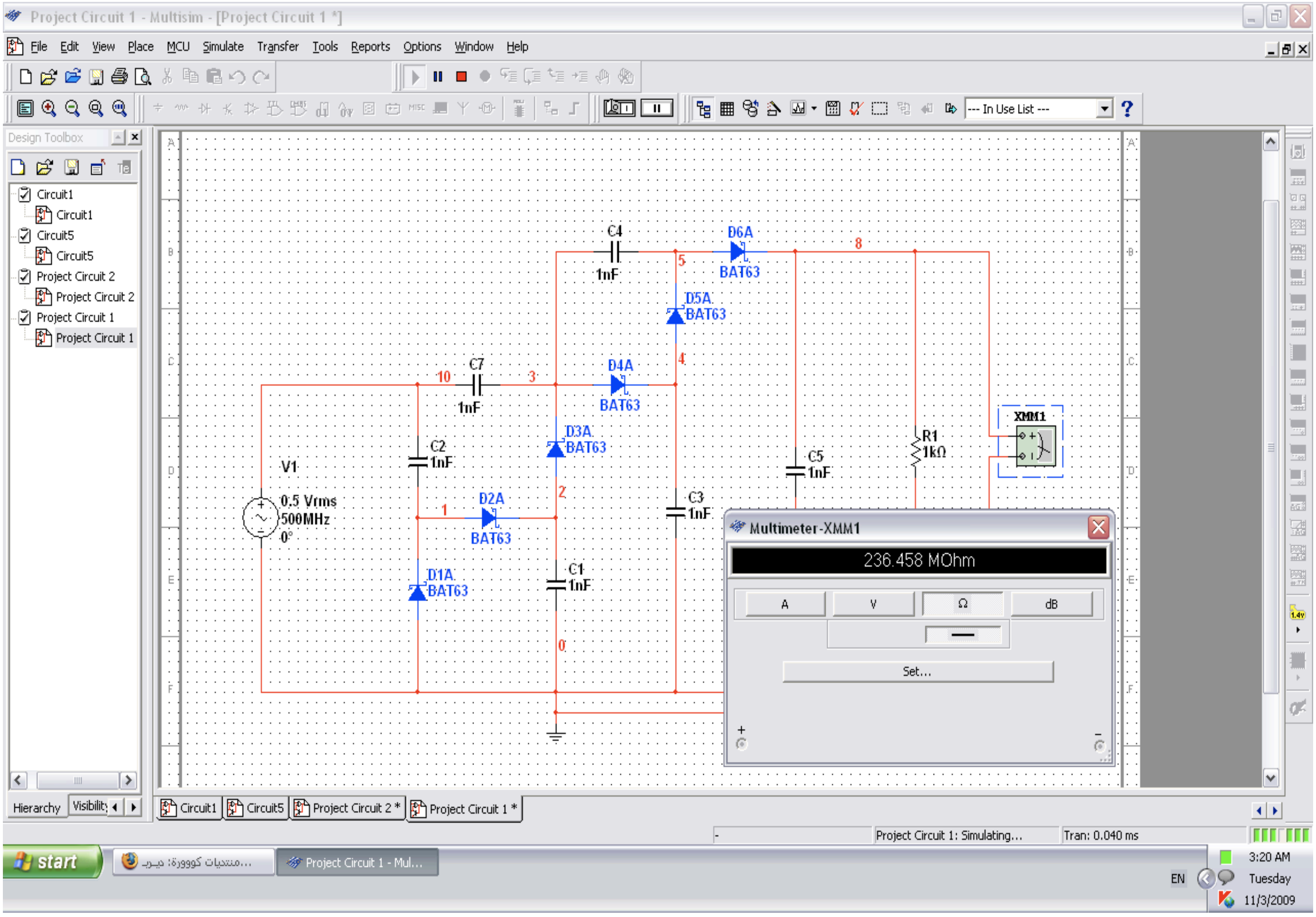

Figure 7: 500 MHz with 236.458 MOhm

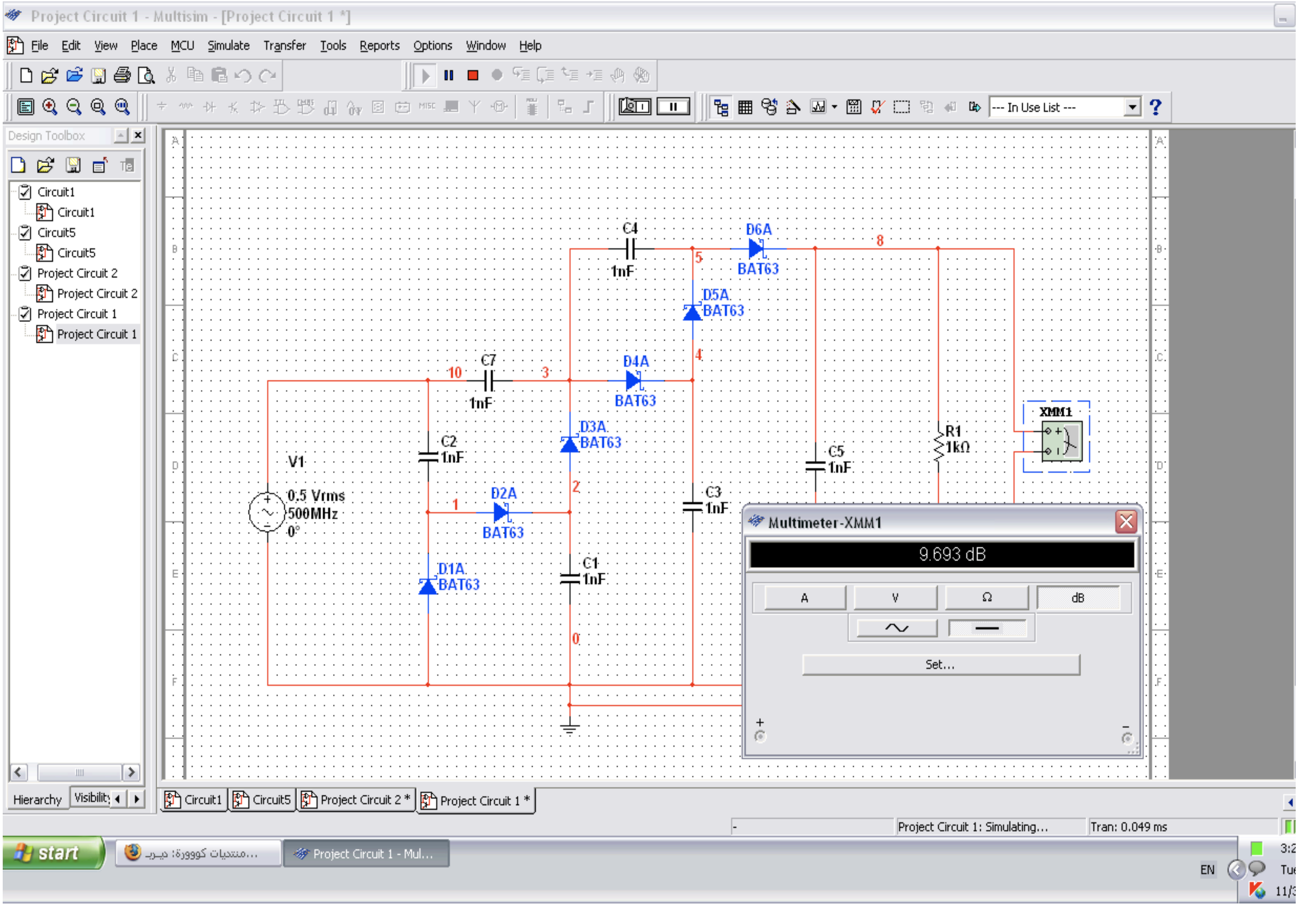

Figure 8: 500 MHz with 9.693 dB

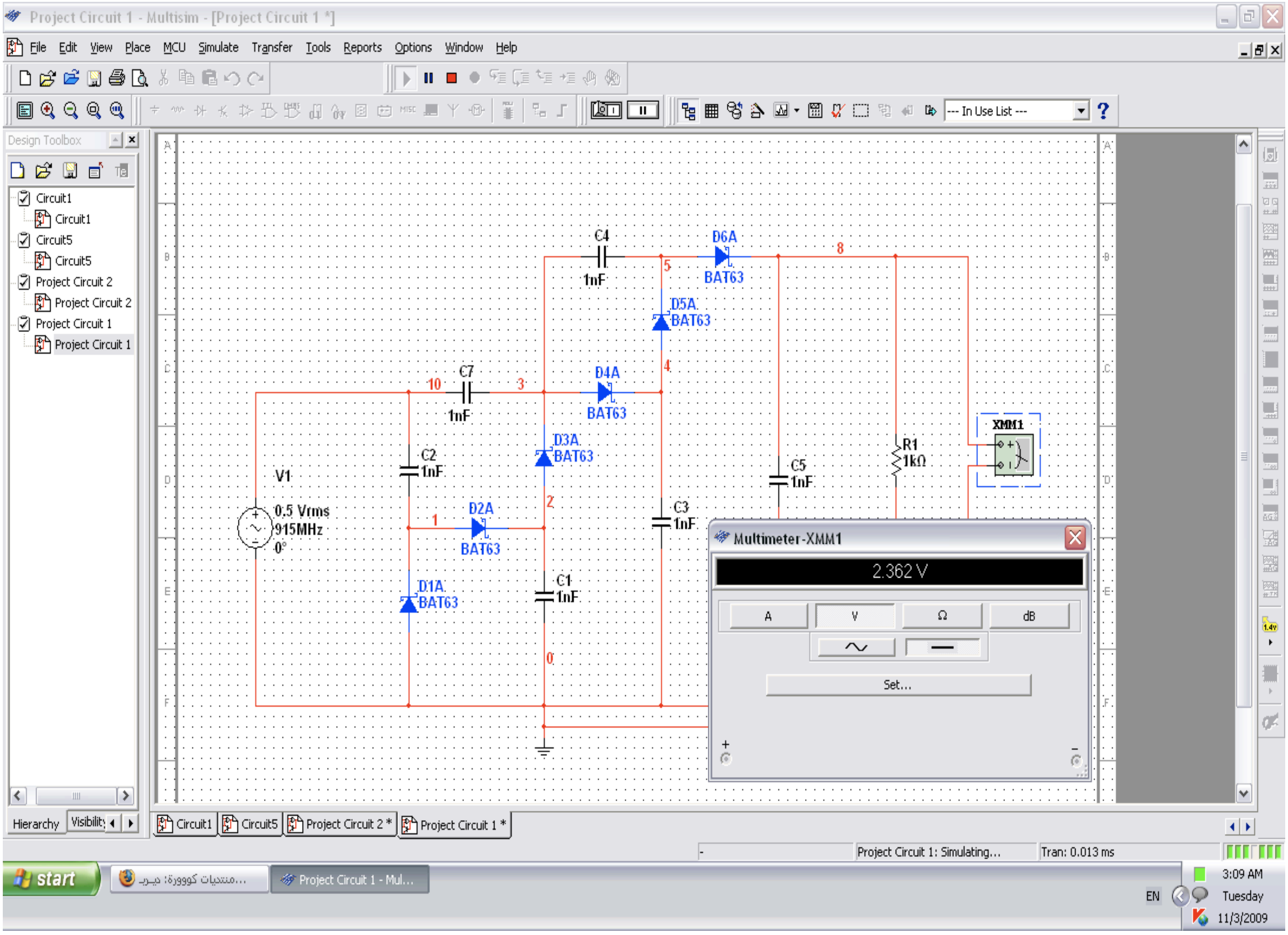

Figure 9: 915 MHz with 2.362 V

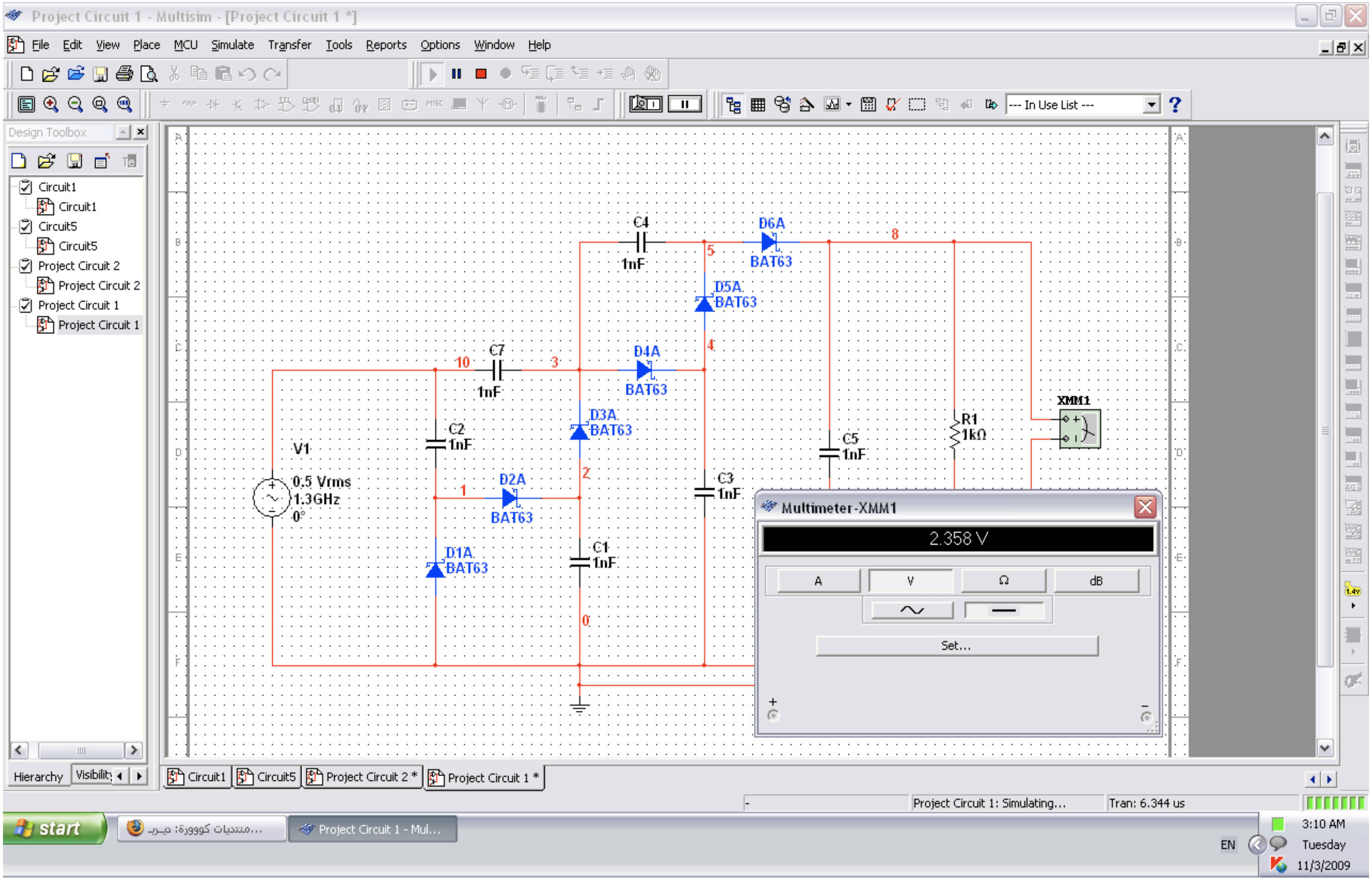

Figure 10: 1.3 GHz with 2.358 V

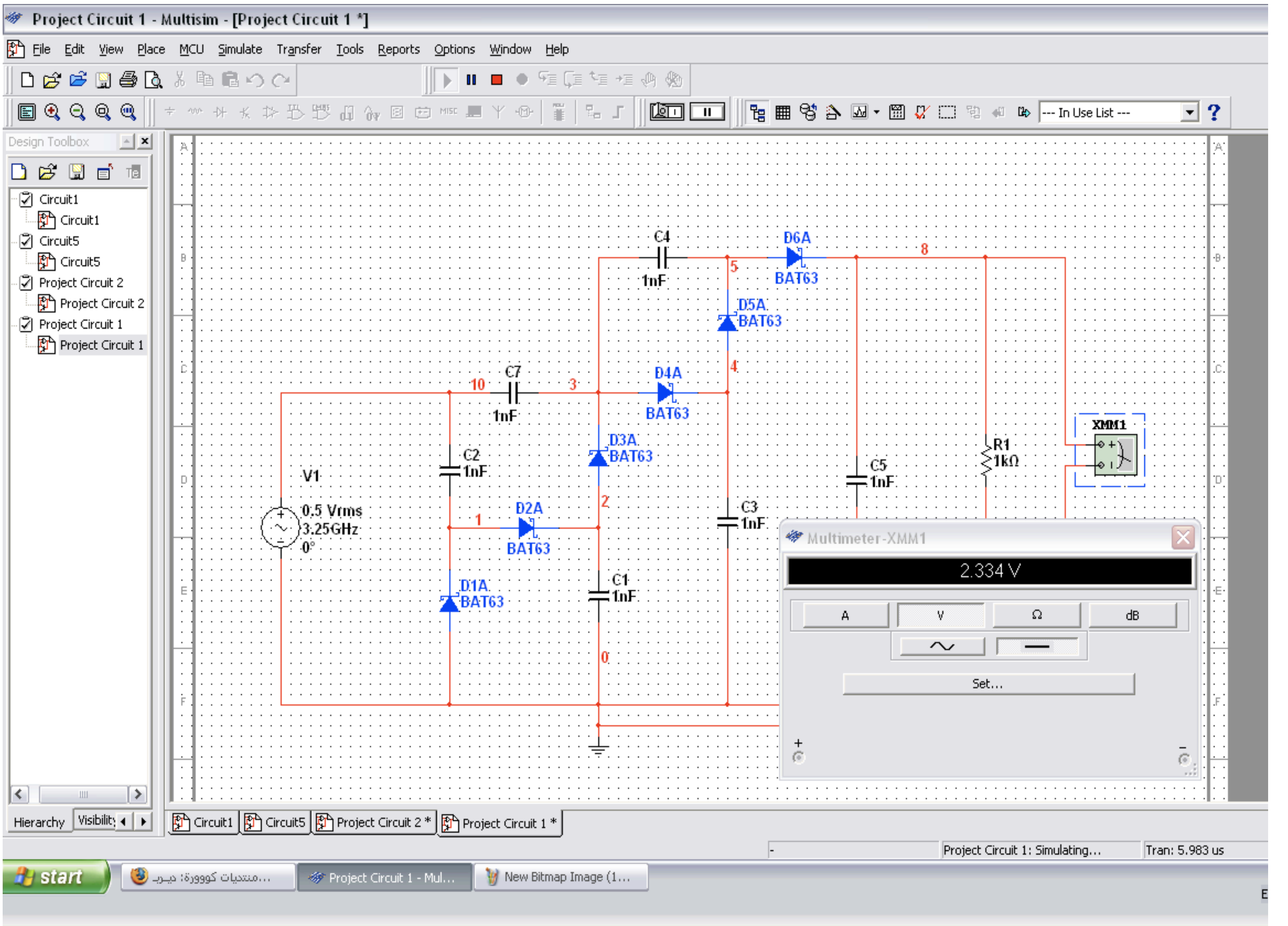

Figure 11: 3.25 GHz with 2.334 V

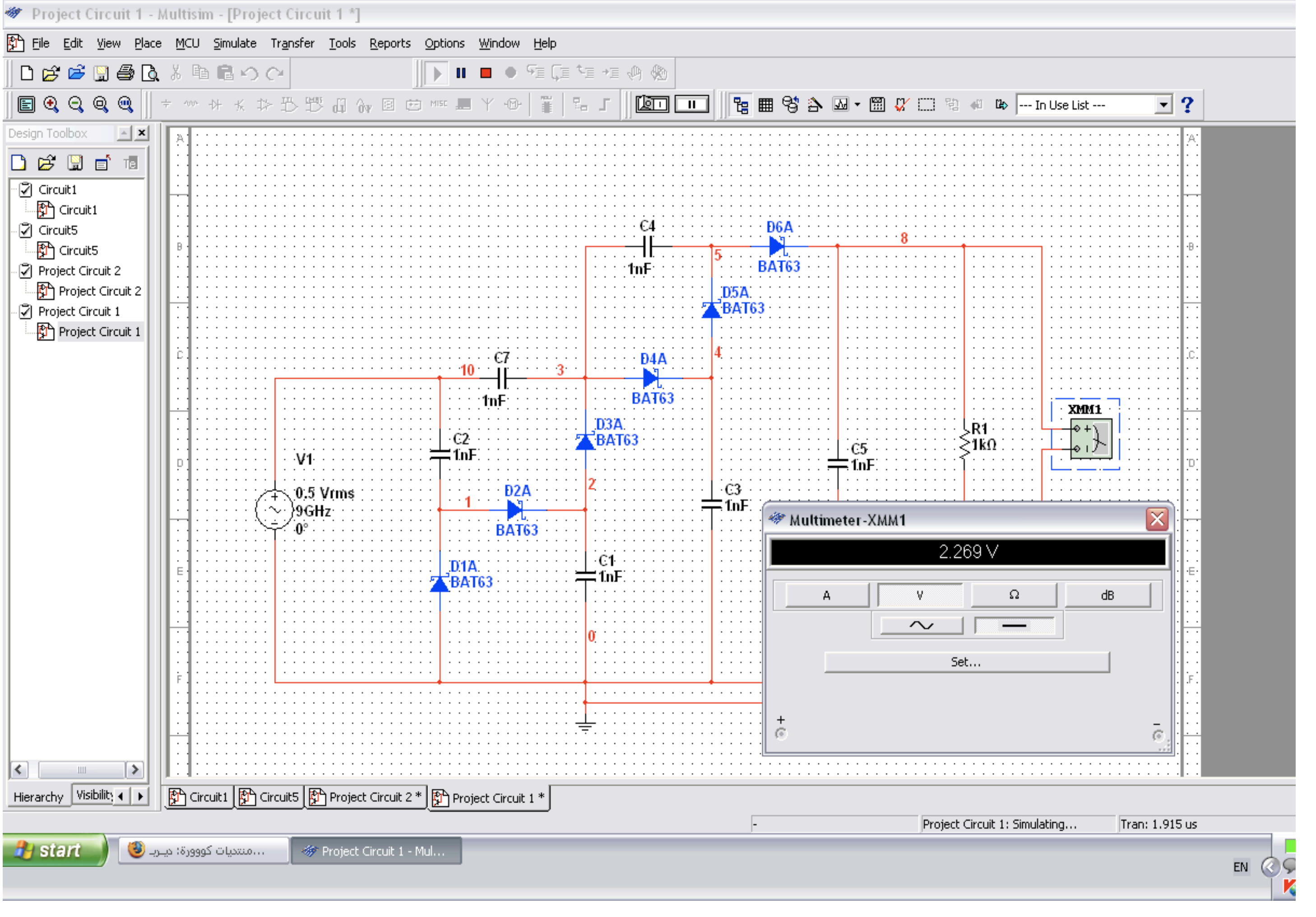

Figure 12: 9 GHz with 2.269 V

For 9 stage circuit:

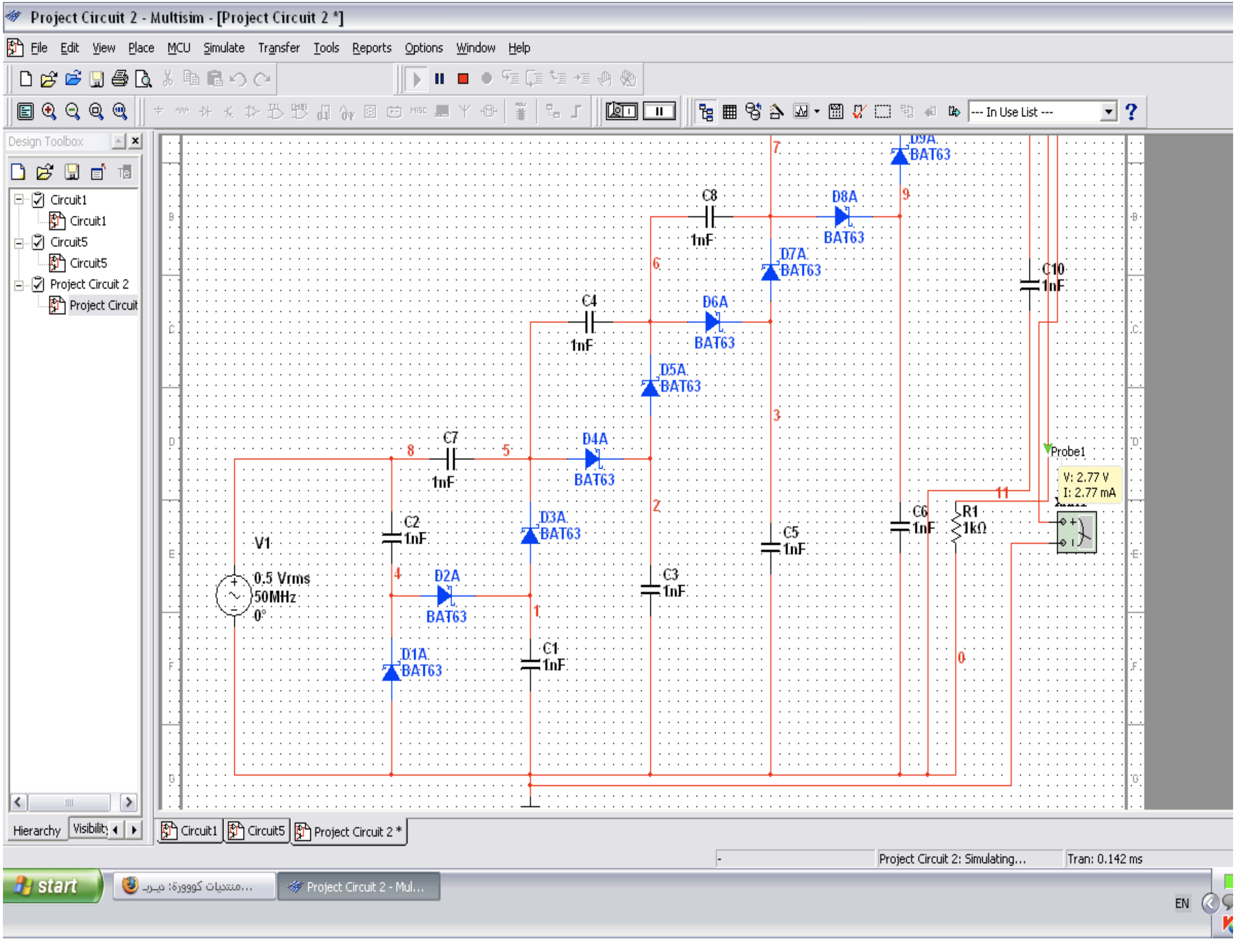

Figure 13: 50 MHz with 2.77 V

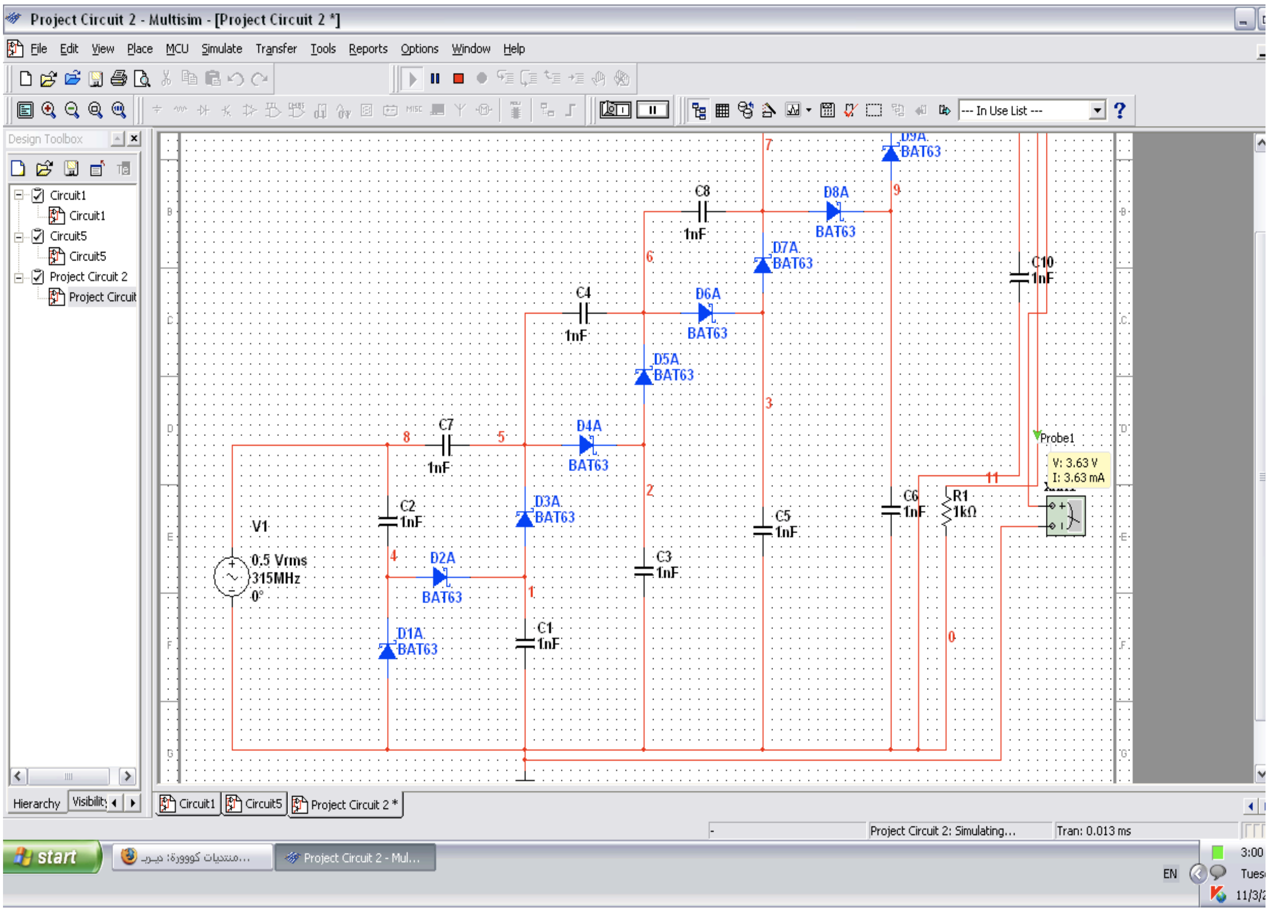

Figure 14: 315 MHz with 3.63 V

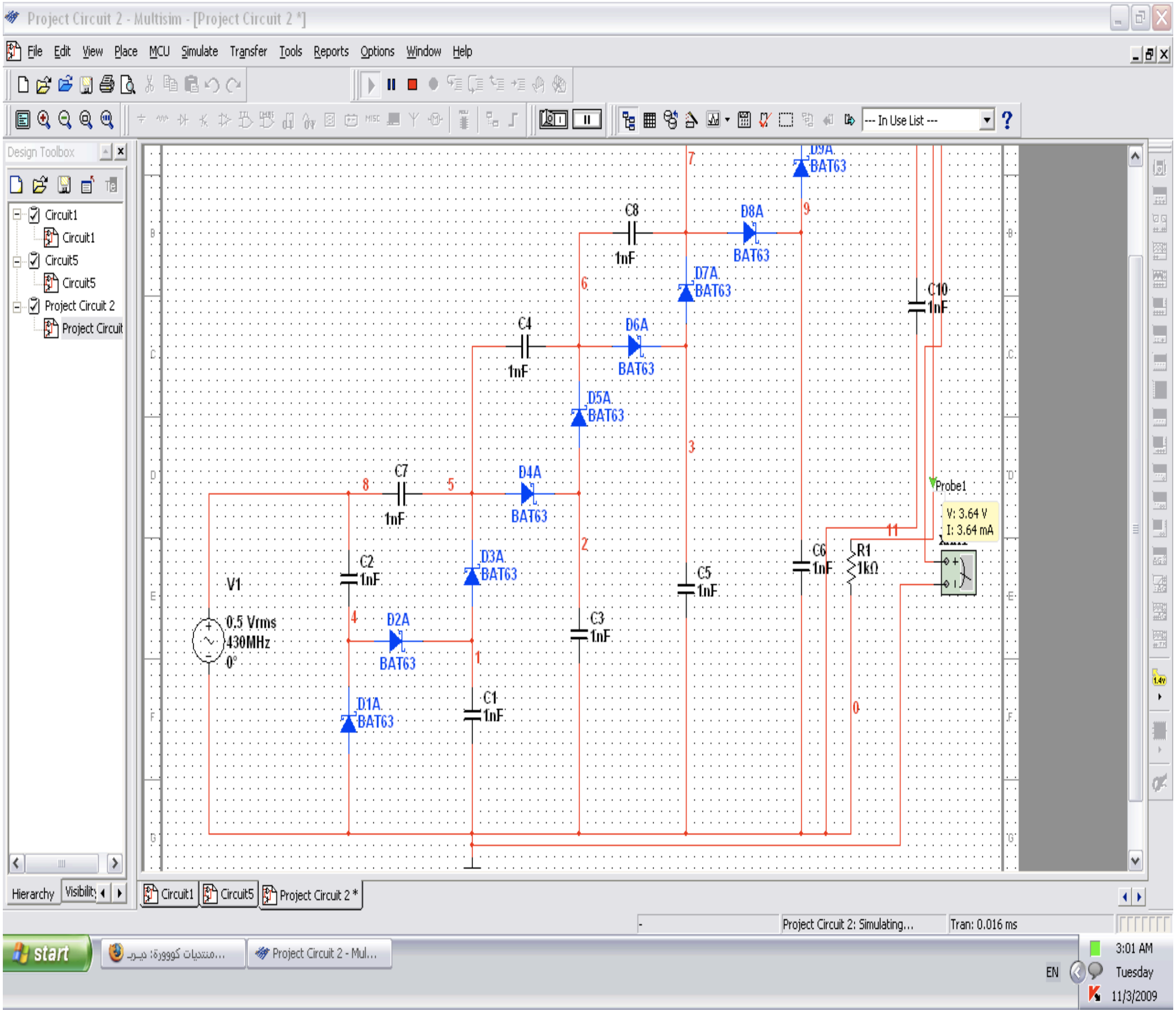

Figure 15: 430 MHz with 3.64 V

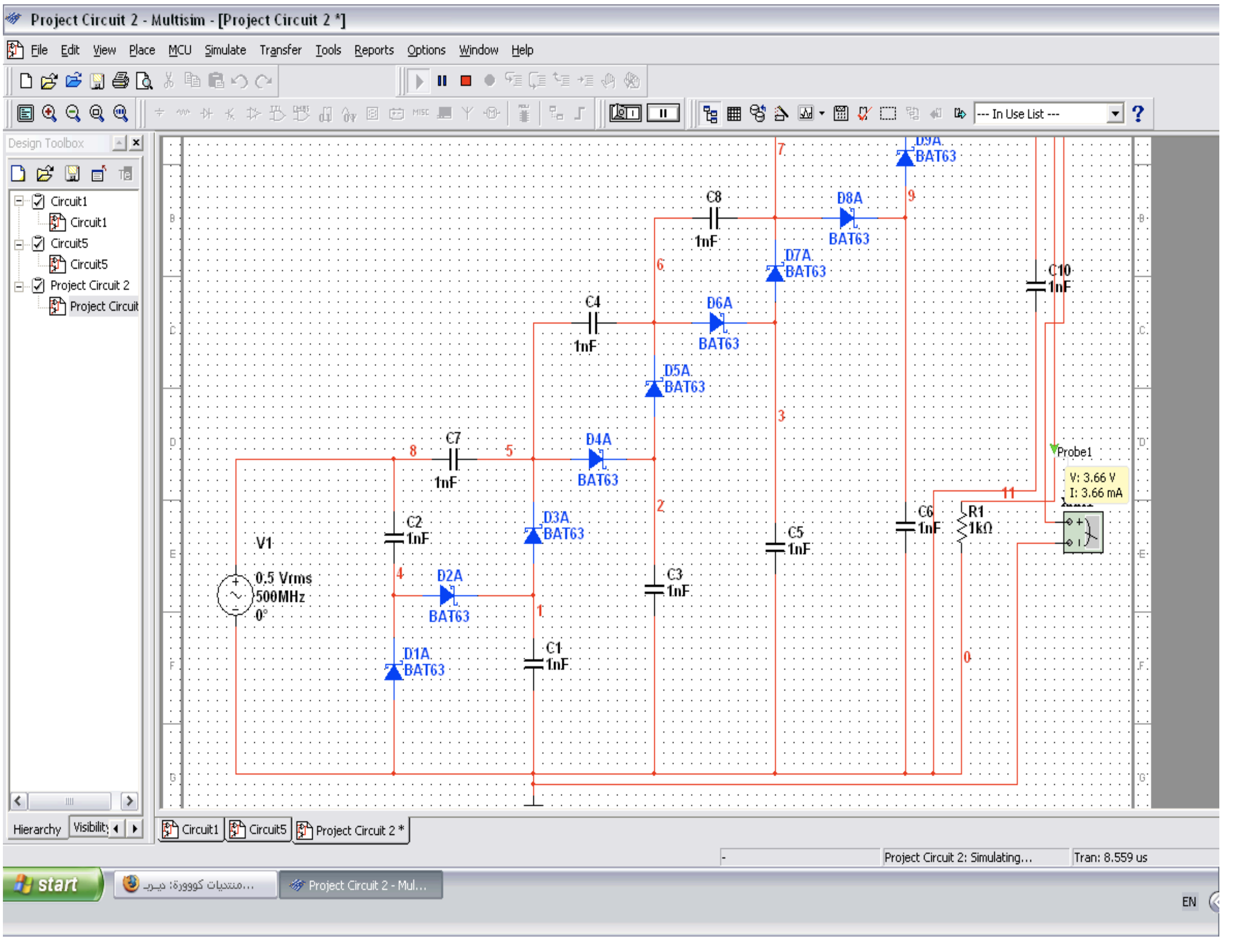

Figure 16: 500 MHz with 3.66 V

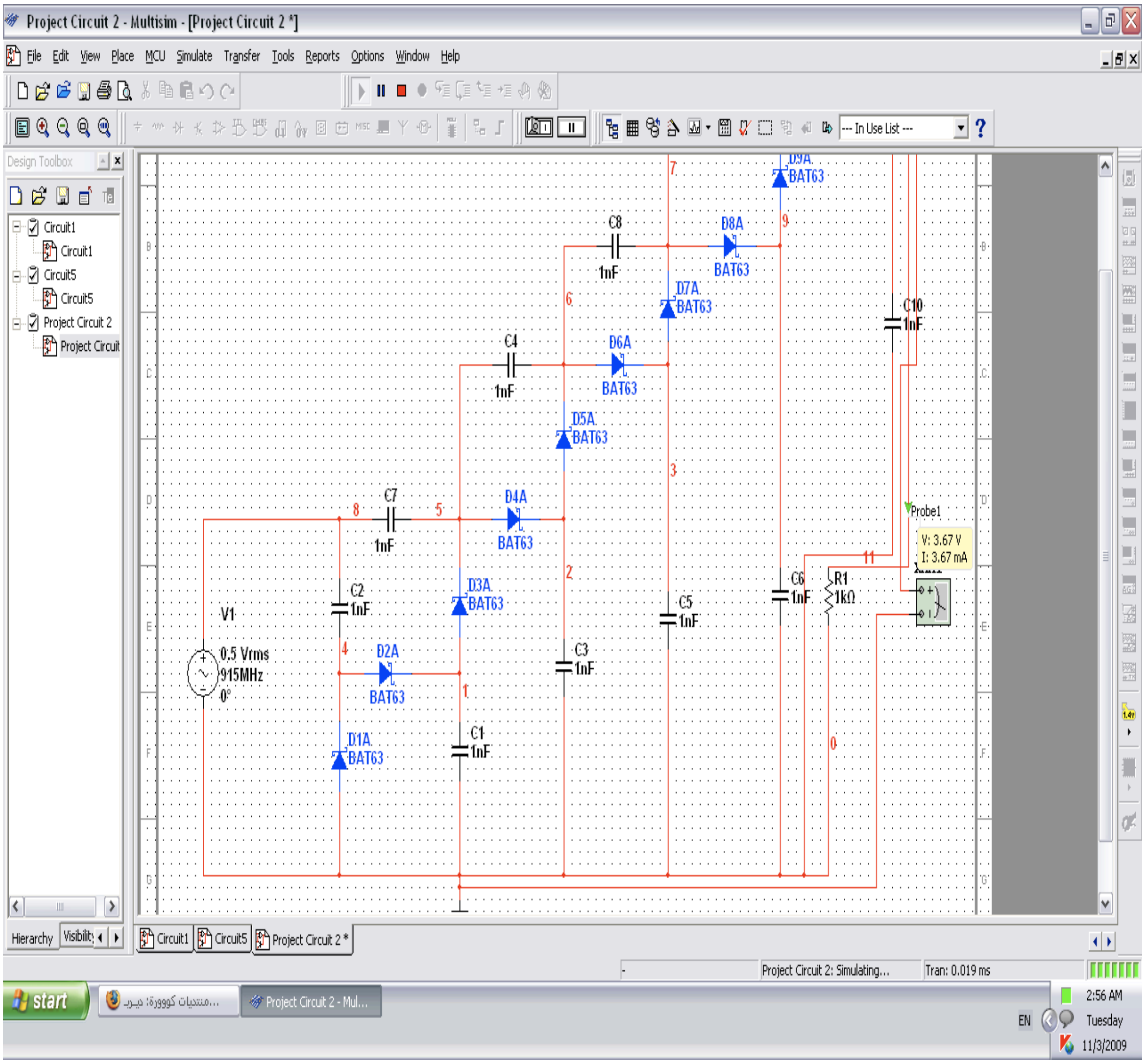

Figure 17: 915 MHz with 3.67 V

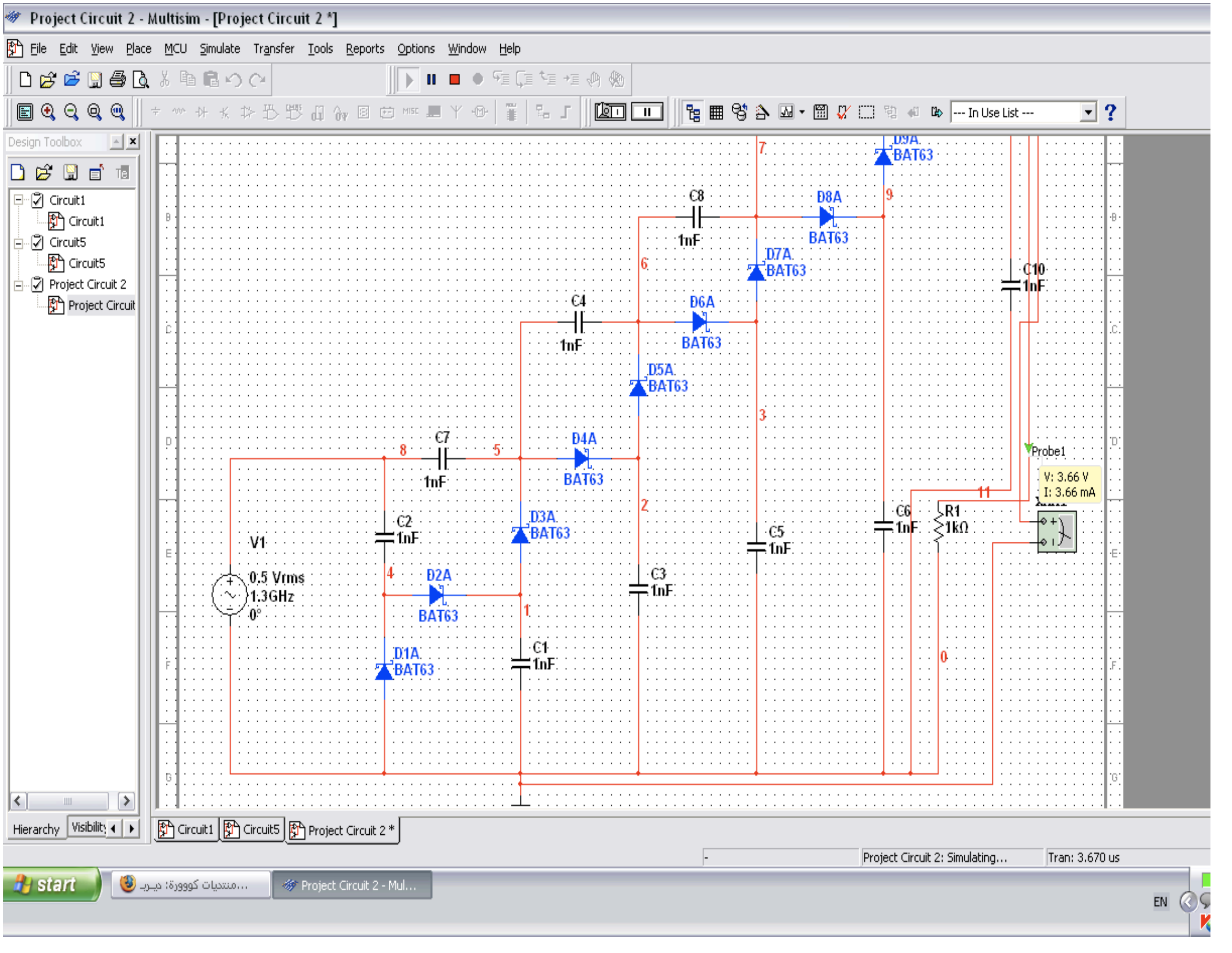

Figure 18: 1.3 GHz with 3.66 V

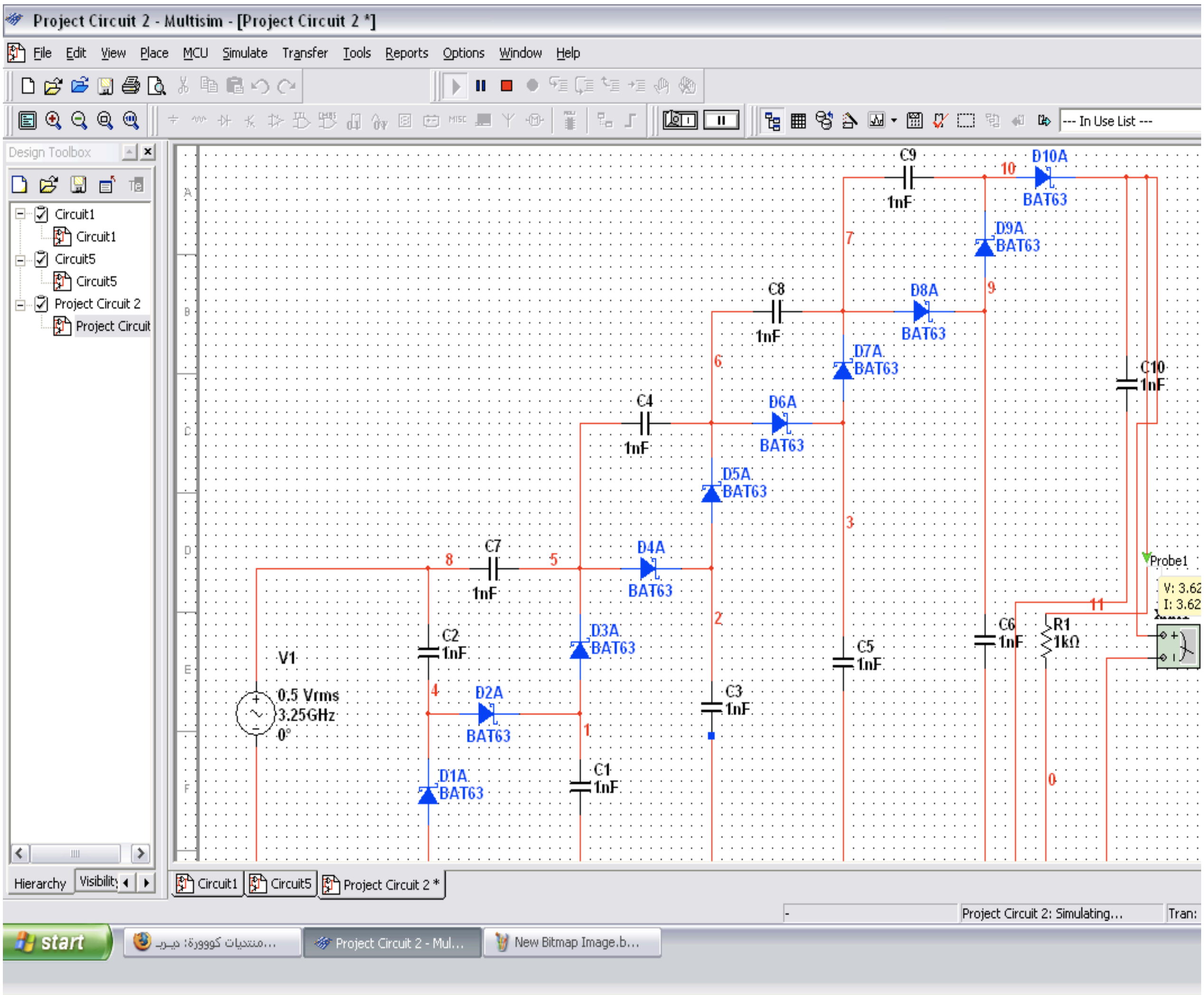

Figure 19: 3.25 GHz with 3.62 V

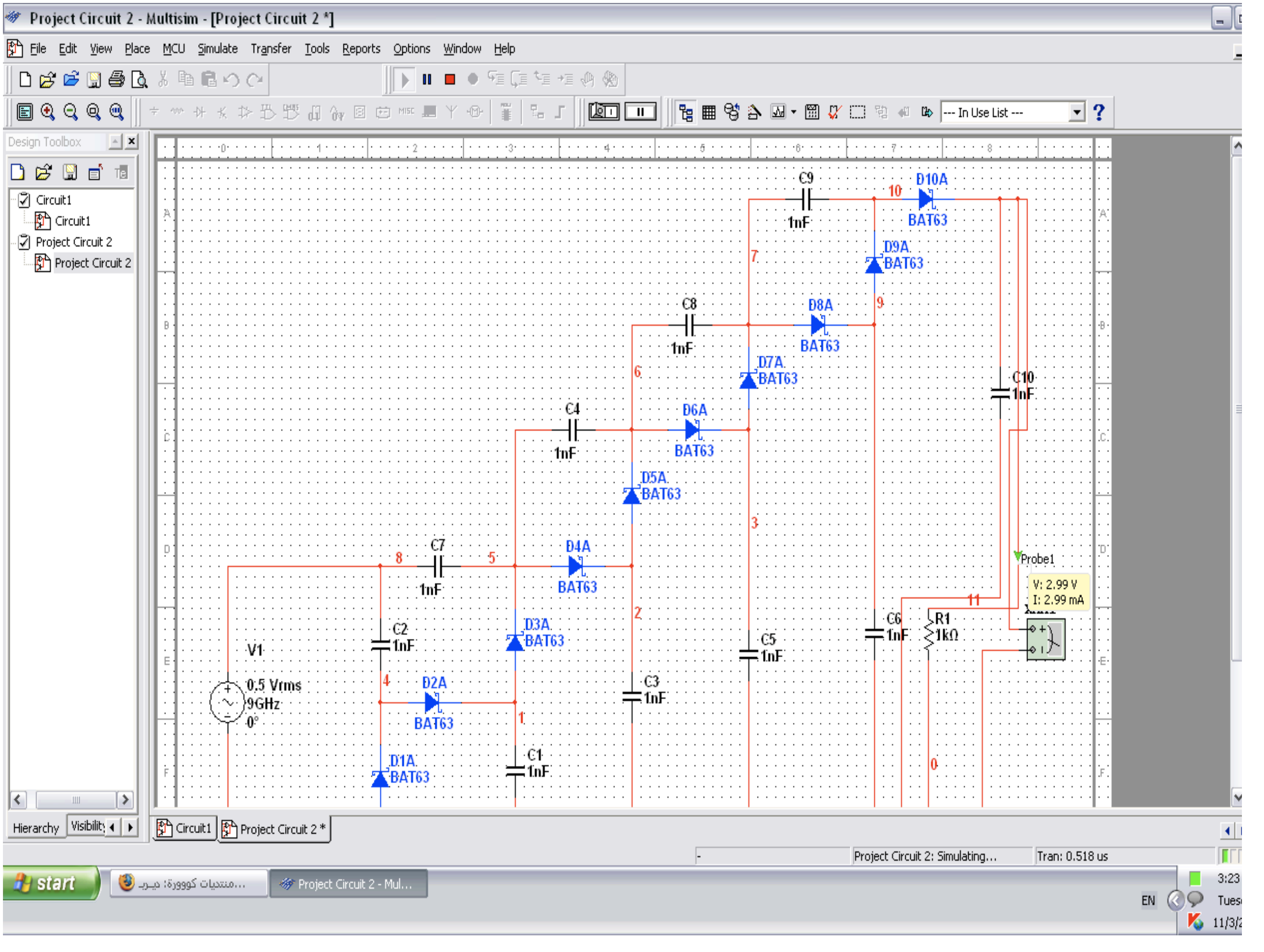

Figure 20: 9 GHz with 2.99 V

For 13 stage circuitry:

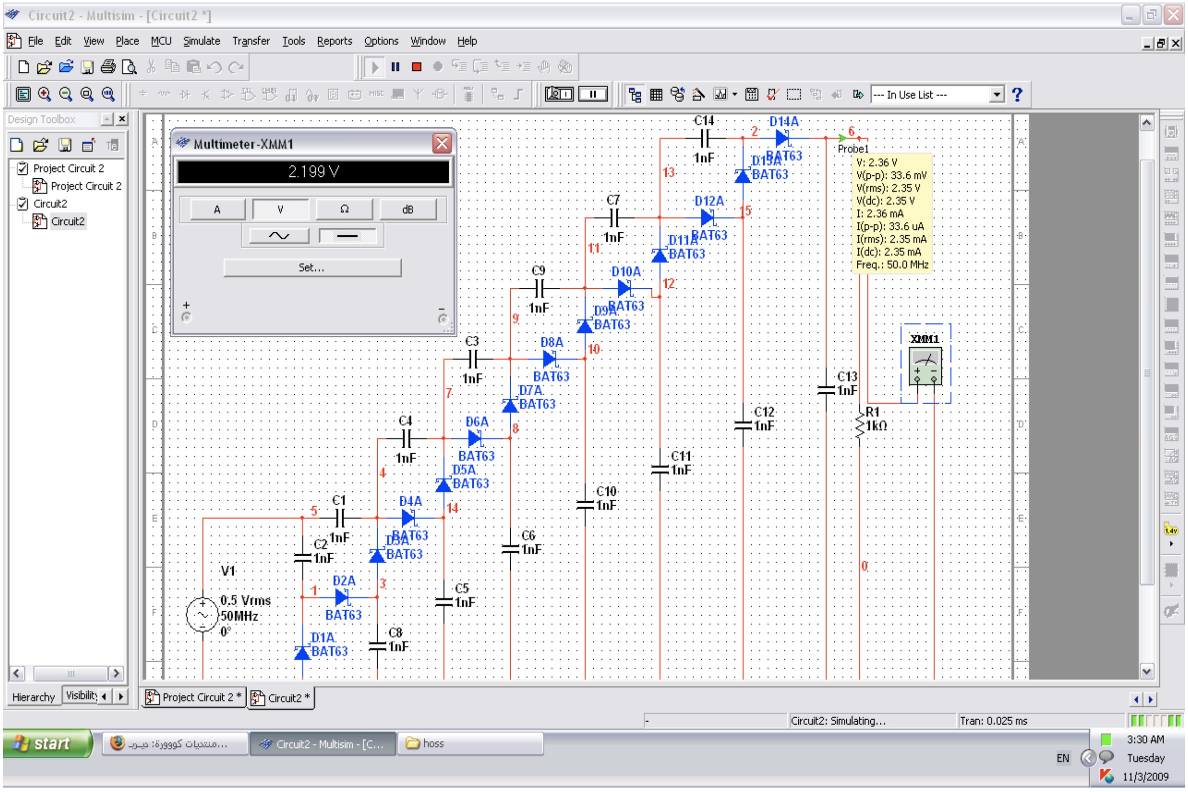

Figure 21: 50 MHz with 2.199 V

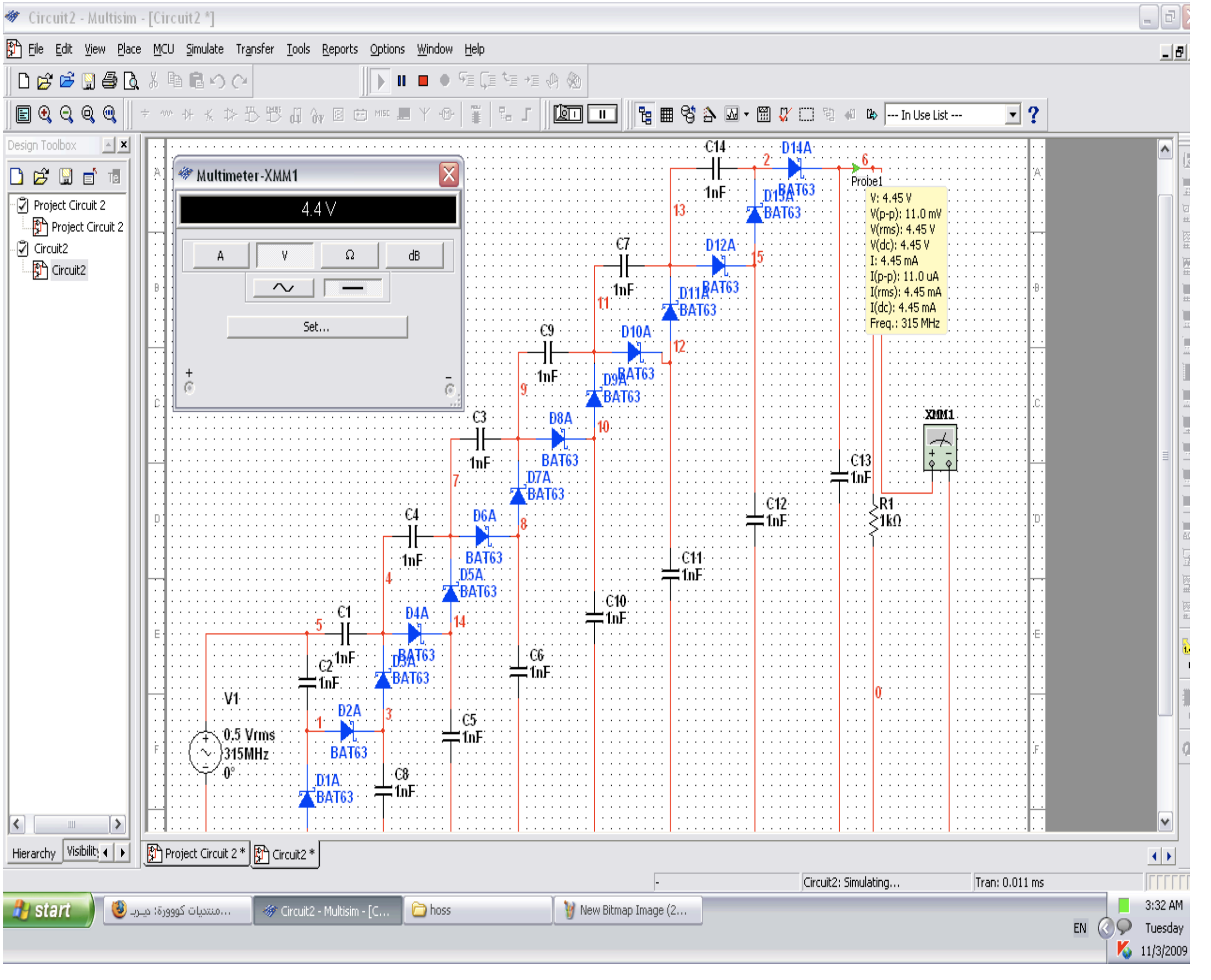

Figure 22: 315 MHz with 4.4 V

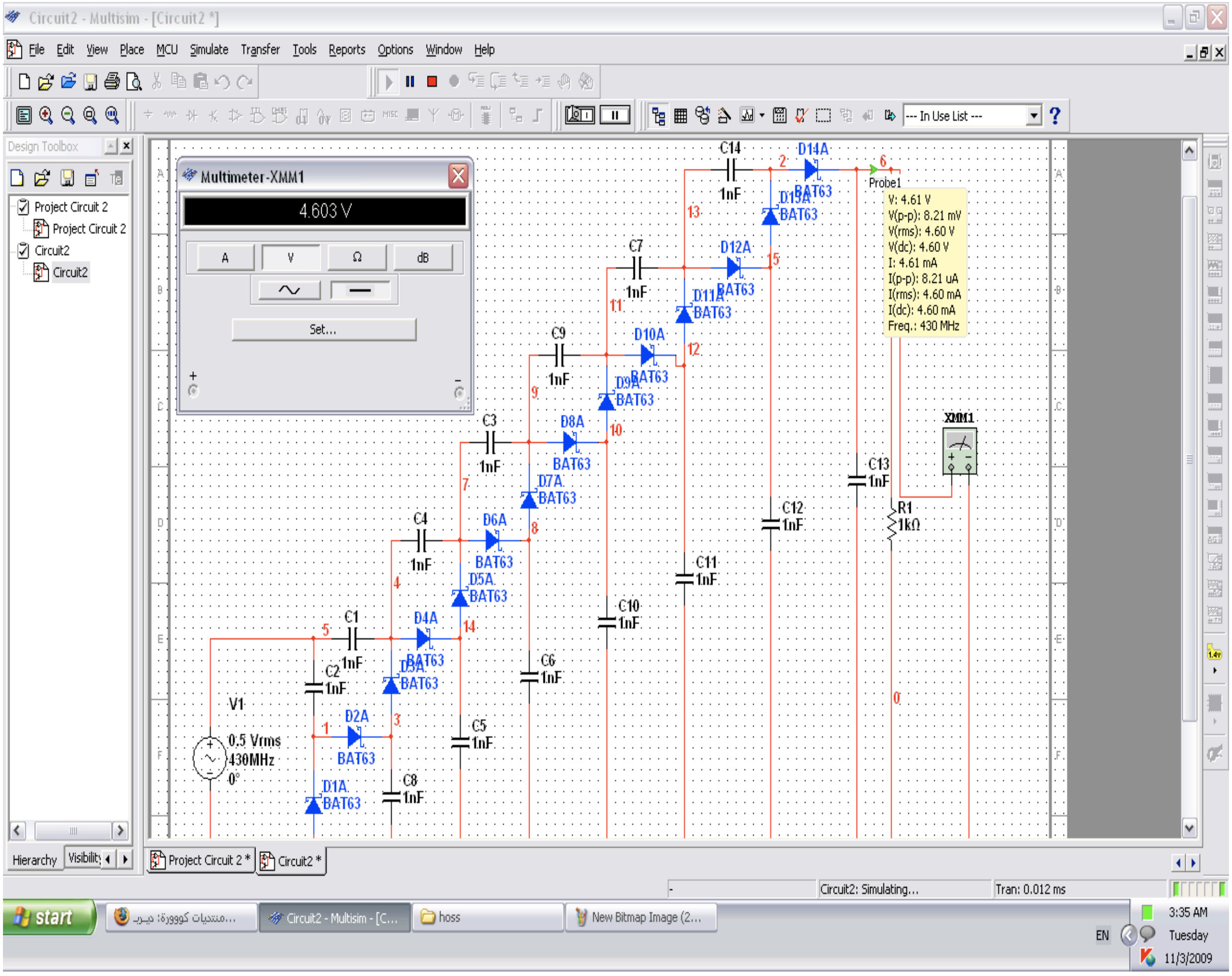

Figure 23: 430 MHz with 4.6 V

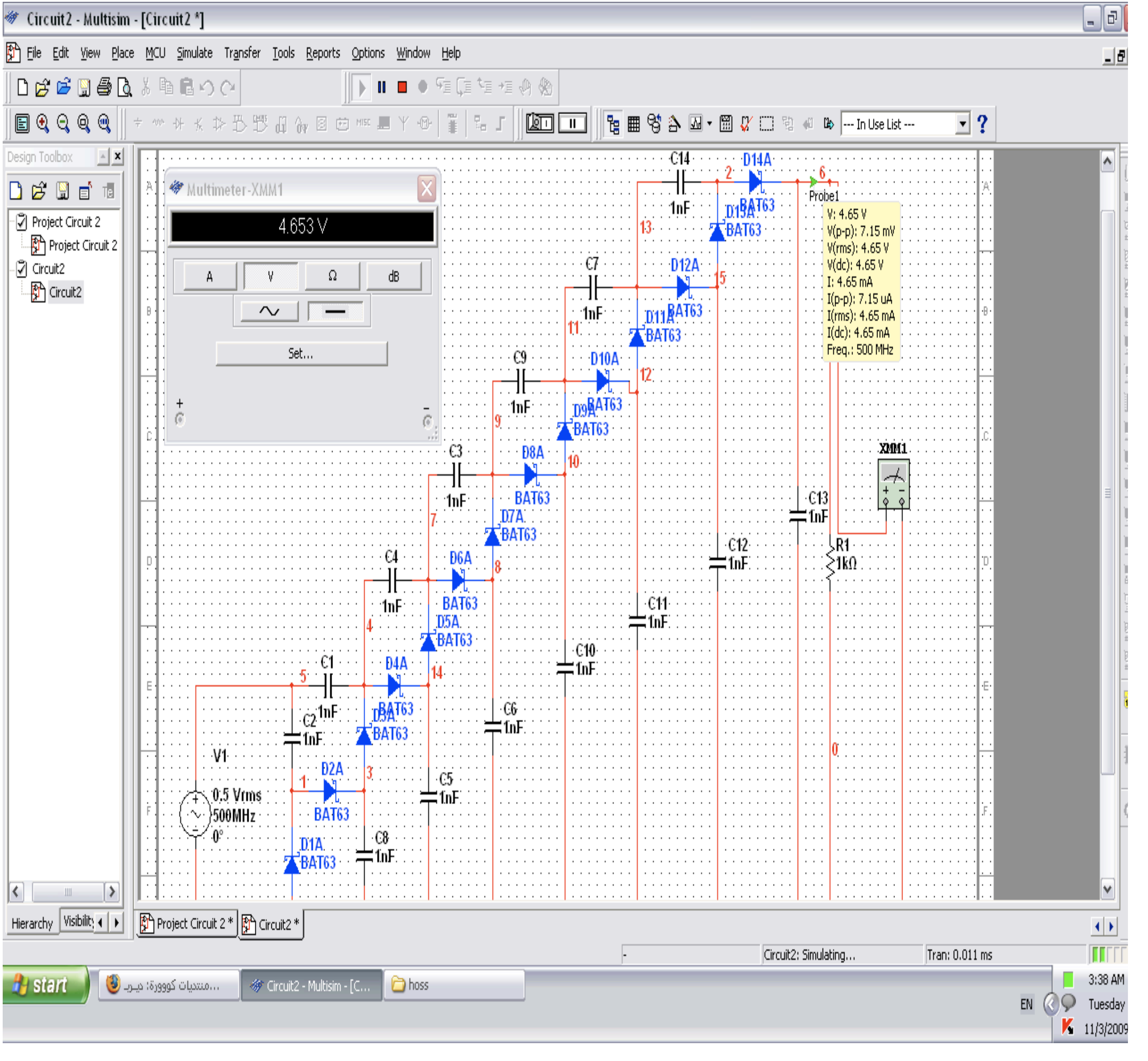

Figure 24: 500 MHz with 4.653 V

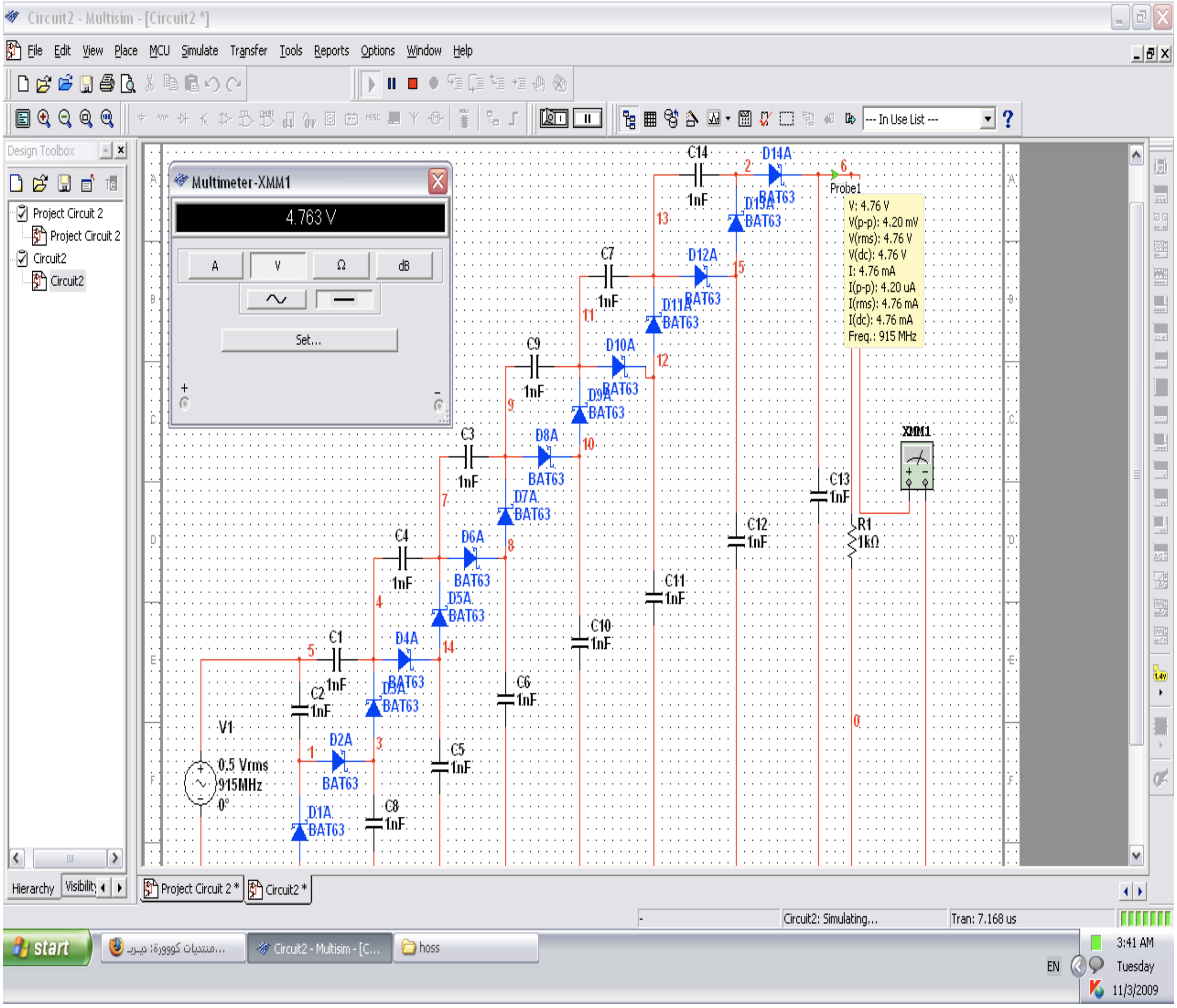

Figure 25: 915 MHz with 4.763 V

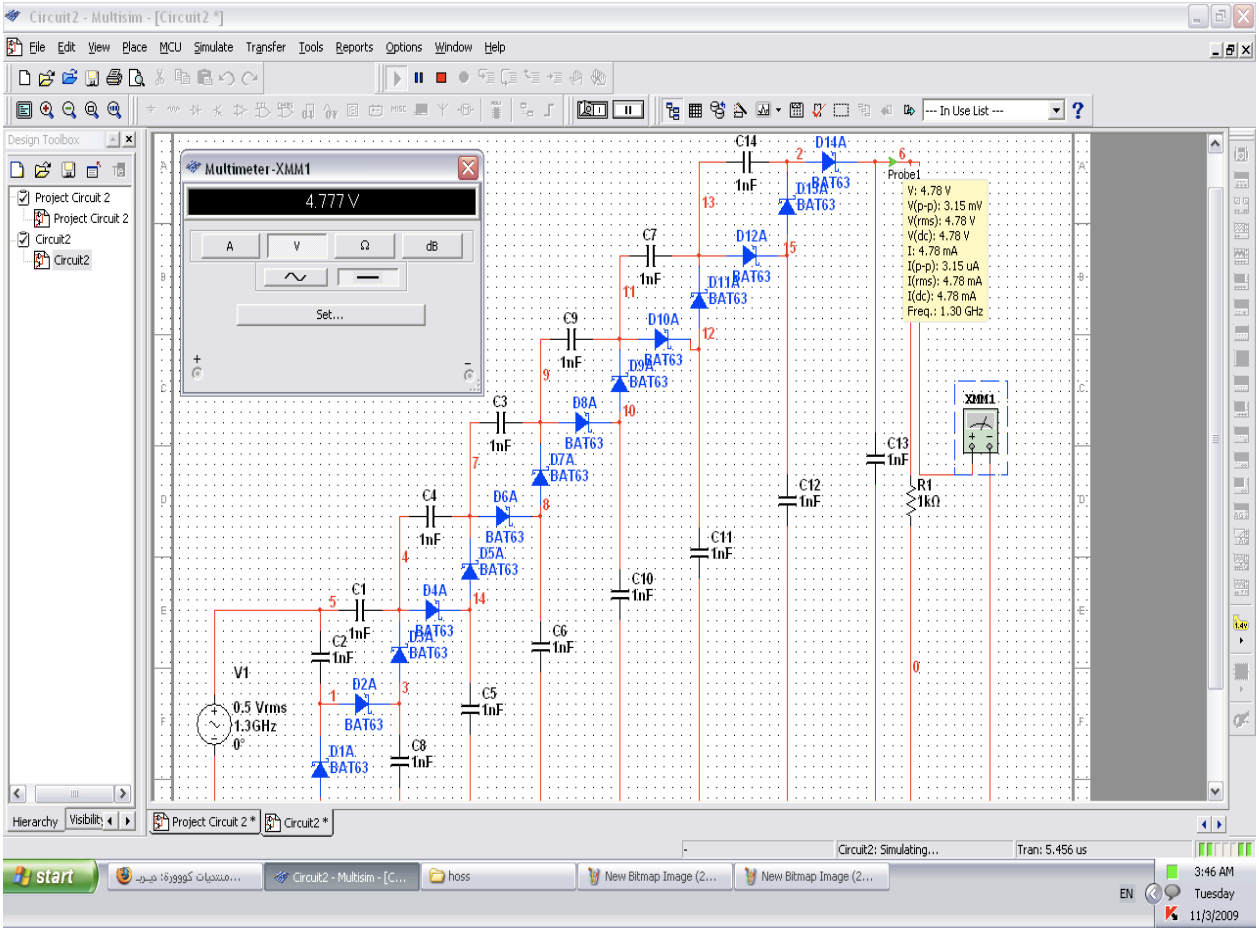

Figure 26: 1.3 GHz with 4.777 V

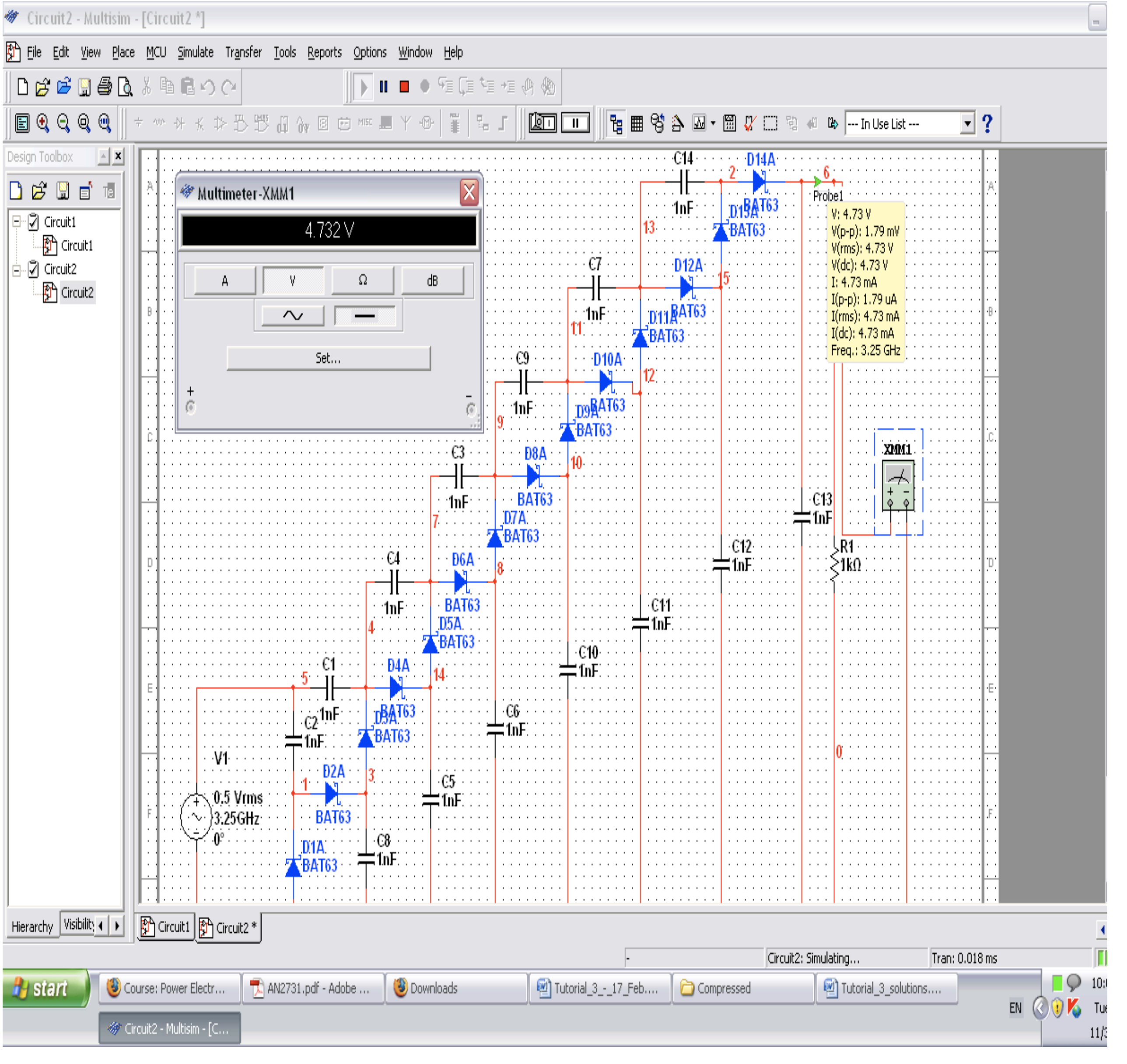

Figure 27: 3.25 GHz with 4.732 V

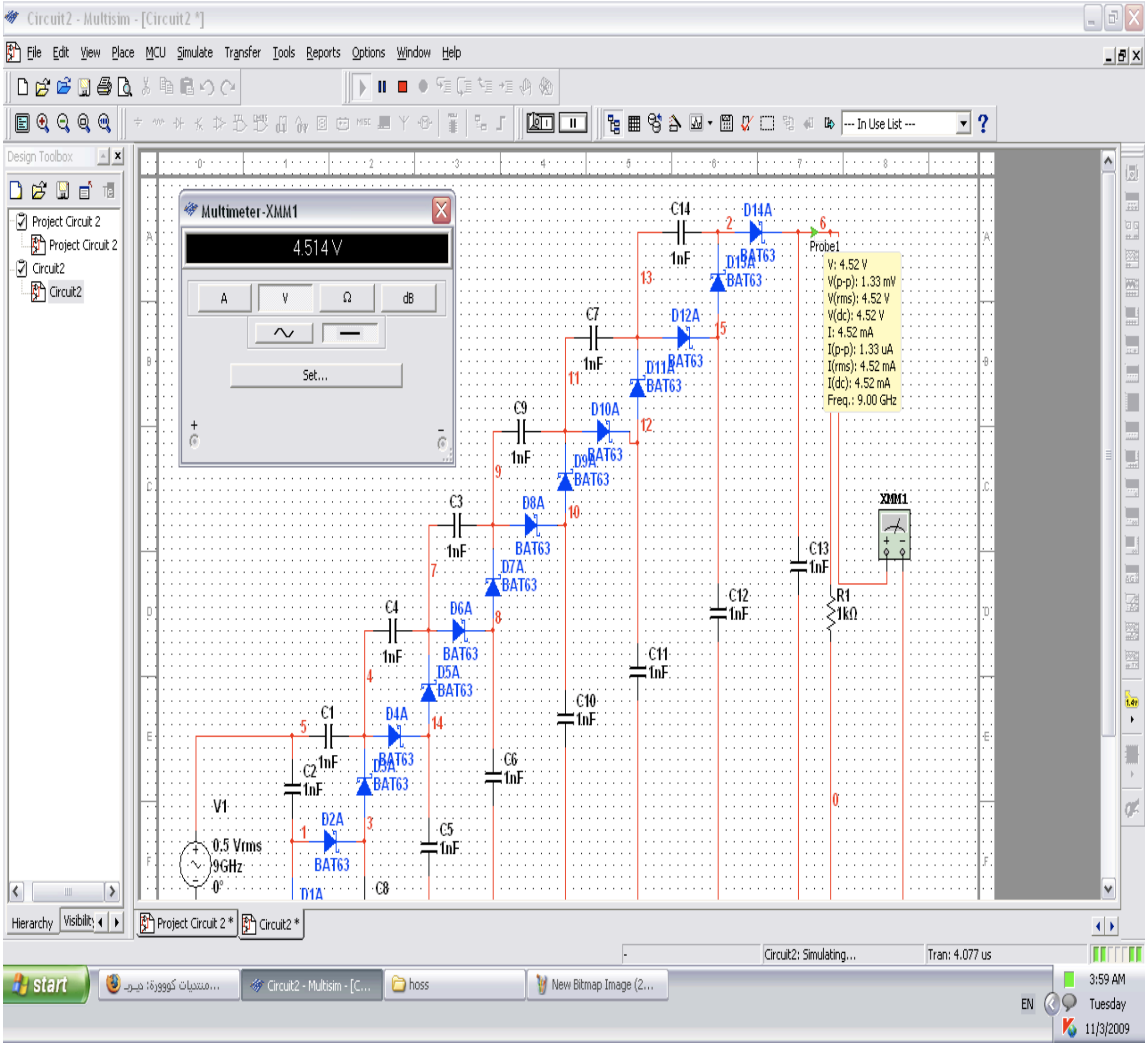

Figure 28: 9 GHz with 4.514 V

Based on these results, it was concluded that:

- 500 MHz is the most suitable frequency for a 3-stage circuit model with 2.365 volts, before it drops with 915 MHz to 2.362 volts.
- 915 MHz is the best model for a 9-stage circuit model with 3.67 volts before it returns to 3.66 volts at 1.3 GHz.
- 1.3 GHz and 3.25 GHz are the most efficient with 4.7 volts for a 13-stage circuit model which is considered a revolutionary step to obtain such high voltage with available frequencies like 1.3 GHz and 3.25 GHz.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

Energy harvesting is a gigantic technology that can make a revolution in the new century. It is important to note that radio frequency energy harvesting is a relatively new area of research within the field of electrical engineering. As a result of the unproven capabilities of the technology, the project's interest came about as a result of its potential for using it to power electronic devices.

To date, RF energy harvesting technology has focused mostly on low-powered applications. However, as the efficiency of the designed harvesting circuitry is increased, use with device's requiring high power demands, becomes a possibility. A high efficiency also allows for the possibility of harvesting ambient radio frequency energy to power certain wireless devices. The goal of this project is successfully achieved by finding new ways to harvest ambient energy from high frequencies and providing solutions to increase the efficiency of the designed harvesting circuitry.

According to Dr. Marlin H. Mickle, Professor of Electrical Engineering at the University of Pittsburgh and researcher in the area of wireless networks and energy harvesting, "When we talk about ambient [radio frequency] energy…we're showing that we can make it work".

It is recommended to use a program called High Frequency Simulation Software (HFSS), which can provide better results with higher frequencies. Moreover, the project faced a problem of unavailable Schottky diode components with the required specifications that affected the hardware part and delayed the prototype model. Therefore, it is recommended to have exactly all the specified components to have better practical results. In addition to that, the receiving part can be modified by implementing a monopole or microstip antenna that can work efficiently on a specified frequency to produce higher power to the rectification circuit than the one achieved in this project.

Finally, this project is considered a revolutionary step for an extremely new technology that should be followed by more advanced steps to improve the efficiency, output power and size of Radio Frequency Energy Harvesting model.

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