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INVESTIGATING TECHNIQUES AND RESEARCH TRENDS IN RF ENERGY HARVESTING

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ABSTRACT

For more than two decades, there were extensive research activities towards harnessing the energy captured from the natural resources and use it for human utility. This field of research, commonly known as energy harvesting, has various characteristics and subsidiary applications. Presently, it is seen that use of mobile phones are increasing due to the advancement of communication systems and numerous services incorporated within it make the availability of free RF signals. This paper discusses various techniques and attempts initiated by research community in harnessing this free RF signals for the purpose of energy harvesting to power up low-powered electronic devices and embedded systems. It also presents some of the most significant research procedures that use RF signals for harvesting energy and their implausible research gap.

Keywords: Energy Harvesting, Energy Scavenging, RF-Signals, Wireless Charging.

1. INTRODUCTION

Radio Frequency (RF) energy [1] is currently broadcasted from billions of radio transmitters around the world, including mobile telephones, hand-held radios, mobile base stations, and television / radio broadcast stations. The ability to harvest RF energy, from ambient or dedicated sources, enables wireless charging of low-power devices and has resulting benefits to product design, usability, and reliability [2]. Battery-based systems can be trickle charged to eliminate battery replacement or extend the operating life of systems using disposable batteries. Battery-free devices can be designed to operate upon demand or when sufficient charge is accumulated. In both the cases, these devices can be free of connectors, cables, and battery access panels, and have freedom of placement and mobility during charging and usage.

RF energy can be used to charge or operate a wide range of low-power devices. At close range to a low-power transmitter, this energy can be used to trickle charge a number of devices including Global Positioning System (GPS) or Real-Time Locating System (RTLS) tracking tags, wearable medical sensors, and consumer electronics such as e-book readers and headsets. At longer range the power can be used for battery-based or battery-free remote sensors for Heating, Ventilation, and Air Conditioning (HVAC) control and building automation, structural monitoring, and industrial control. Depending on the power requirements and system operation, power can be sent continuously, on a scheduled basis, or on-demand. In large-scale sensors deployments significant labor cost avoidance is possible by eliminating the future maintenance efforts to replace batteries.

Ambient radio waves are universally present over an ever-increasing range of frequencies and power levels, especially in highly populated urban areas. These radio waves represent a unique and widely available source of energy if it can be effectively and efficiently harvested. The growing number of wireless transmitters is naturally resulting in increased RF power density and availability. Dedicated power transmitters further enable engineered and predictable wireless power solutions. With continued decreases in the power consumption of electronic components, increased sensitivity of passive receivers for RF harvesting, and improved performance of low-leakage energy storage devices, the applications for wire-free charging by means of RF-based wireless power and energy harvesting will continue to grow. The charging of mobile devices is convenient because the user can do it easily, like for mobile phones using external charger. But for other scenarios, like mobile nodes which are located in difficult to access environments, the charging of the batteries remains a major problem. This problem increases when the number of devices is large and are distributed in a wide area or located in inaccessible places. The research on RF energy harvesting provides reasonable techniques of overcoming these problems. Reducing power consumption has become a major challenge in mobile device. As a vital factor affecting system cost and lifetime, energy consumption in mobile devices is an emerging and active research area. The energy consumption of mobile nodes is of crucial concern due to the limited availability of energy. While energy is a scarce resource in every mobile device, the problem is more severe for the following reasons: (i) compared to the complexity of the task they carry out; sensing, processing, self-managing, and communication, the nodes are very small in size to accommodate high-capacity power supplies, (ii) though the research community is investigating the contribution of renewable energy and self recharging mechanisms, the size of nodes is still a constraining factor, and (iii) ideally, a mobile node consists of a large number of sub-nodes. This makes manually changing, replacing or recharging batteries almost impossible. This paper surveys the various trends, current research direction, and excavating research gap in RF energy harvesting.

2. ENERGY HARVESTING

The term ‘energy harvesting’ can be defined as a method to derive an alternate source of energy from various external sources. Such external sources can be thermal energy, salinity gradient, solar energy, and kinetic energy. Such energy are reposited (or stored) in miniature electronic and electrical devices which are usually positioned in energy source points. The phenomenon of energy harvesting furnishes very less amount of energy. Usually, such energy is captured from the surroundings, which is also known as ambient energy that is completely free of cost [3]. The categorization of the energy harvesting can be done depending on the energy that the application is trying to use. Table 1 highlights some of the common energy harvesting mechanisms along with their energy generation capabilities [3].

Table 1: Energy Harvesting Sources

Harvesting Method	Energy Generation capability
Solar Cells	16mW/cm^3
Piezoelectric	335mW/cm^3
Vibration	118mW/cm^3
Thermoelectric	42mW/cm^3

The noted researcher Fry in his work [4] has featured some of the portable energy suppliers. The features discussed by the author for energy harvesting capabilities are (i) higher degree of current and voltage, (ii) power density, (iii) various physical attributes (e.g. shape, size, weight), (iv) various environmental characteristics (e.g. operating temperature, water resistance capabilities, and (v) maintenance characteristics. Different types of standard energy harvesting methods explored and reported in the literature are as follows:

2.1 Electromagnetic Energy Harvesting

This energy harvesting method uses the ideal principle of electromagnetic induction (a method of producing voltage in the conductor by altering the magnetic field surrounding the specific conductor). The work in [5] and [6] discuss the frequent use of permanent magnets along with a coil and resonant cantilever beam. However, the method is not that effective as it can produce a maximum voltage of 0.1 Volt whereas other schemes (e.g. electrostatic/ piezoelectric) can generate a voltage in the range of 2-10 Volts.

2.2 Photovoltaic Cells

Use of photovoltaic cells is a common method of energy harvesting. This technique converts of light energy into electrical energy. It can also be said that the source of such energy is usually sunlight. However, one of the difficulties in this scheme is to install the equipment in such a position (marine location) where there is an abundant sunlight. In case if such positioning is not an issue, then this is one of the cheapest energy harvesting methods. The system is also accompanied by various challenges like effect on the surroundings of the equipment when installed in high latitudes, rainy day, features of the photovoltaic cells deployed, illumination intensity, energy supply requirements etc [7]. The complementary benefit of this approach is that it uses very small dimension equipment. However, there is no guarantee of the spontaneous supply of the energy round the clock due to which the mean energy availability is typically minimal for energy harvesting using this technique.

2.3 Mechanical Vibration Harvesting

This method uses the mechanical vibration and converts it into electrical energy for the purpose of energy harvesting. It is seen that when electronic equipment is subjected to mechanical vibration, an inertial mass can be thought of being deployed for the purpose of movement generation, which is then converted to electrical energy. Usually such mechanisms are deployed in (i) piezoelectric, (ii) electromagnetic, and (iii) electrostatic forms. The piezoelectric materials convert all the mechanical vibration (energy captured from force, pressure, or vibration) into electricity. Therefore, it can be seen that there is a rise of technical adoption of piezoelectric materials for energy harvesting in many research works even most recently. There is a need for mode of storing the energy produced by piezoelectric materials, which will mean that such technique can be deployed either by means of circuit design and can be used for harvesting such energy for different applications. Some of the literature also discuss about storing such energy in various rechargeable batteries for long durations [8]. The characteristic feature of the normal capacitors for discharging instantly renders them inappropriate as the energy storage equipment in computational electronics. The system is also associated with limitations as piezoelectric materials are normally brittle in nature and may lead to charge leakage.

2.4 Capacitive Energy Harvesting

This energy harvesting technique is dependent on the charging capacitance of the vibration-dependent variable capacitors. The plates are segregated for an initial charged variable capacitance and electrical energy is accomplished from mechanical forms. Such techniques make use of electrostatic generators for generating electricity by deploying manual energy. This technique is highly compatible and supportive for micro-electronics as they do not have much external hardware dependency. The limitation of this technique is that it requires supplementary source of voltage for initially charging the specific capacitor [9].

2.5 Thermoelectric Generators

This energy harvesting technique uses thermal energy and converts them to electrical energy for specific applications. The devices that produce thermal electricity essentially are used in space and terrestrial applications. The usage of such techniques is limited owing to the minimal capability of attaining energy efficiencies required for energy harvesting [10].

3. UPCOMING RESEARCH AND ISSUES IN ENERGY HARVESTING

One of the biggest problems in energy harvesting is obtaining the correct sources of energy which are required to be cost effective, available, reliable, and consistent. In the area of wireless networking system, the deployment of energy harvesting methods is eventually encountering various limitations as well as constraints for ensuring the effectiveness of the energy harvesting equipment. The energy requirements of the wireless systems provided by the traditional battery will require conserving the harvested energy for further operations. Hence, there is an exponential need for designing an energy harvesting device that can provide abundant energy for wireless systems in an efficient manner. After reviewing few significant papers [3][11][12], the various research impediments we observed are as follows:

- Development of an artificial energy harvesting equipment that integrates control, sources, and eventually storage systems.
- Designing the hardware and software modules for the purposes of evaluation along with forecasting for energy parameters while harvesting.
- The energy harvesting equipment to work in all the adverse conditions.

Fig. 1: Thermoelectric Nano-Materials

A study by Wake Forest University [14] shows that clothes could be designed from the thermoelectric nano-materials, which has the capability of generating the energy very slowly as well as spontaneously. Hence, thermoelectric energy harvesting is one of the future trends of research where harvesting can be performed very easily. The study suggests that best materials can harvest energy up to 21% using thermoelectric materials. However, one of the evident research issues in this is overcharging of the thermoelectric in higher temperature fluctuations. Therefore, if the surrounding room temperature is equivalent to body temperature, then the energy stream will eventually drop. Hence, it can be concluded that thermoelectricity cannot be considered as the optimal source for electronic devices that continuously require energy supply or more proportion of energy. The study also suggests that thermoelectric energy harvesting can be suitable for embedded medical monitors. Energy hungry applications like mobile phones and laptops should not be using thermoelectric energy.

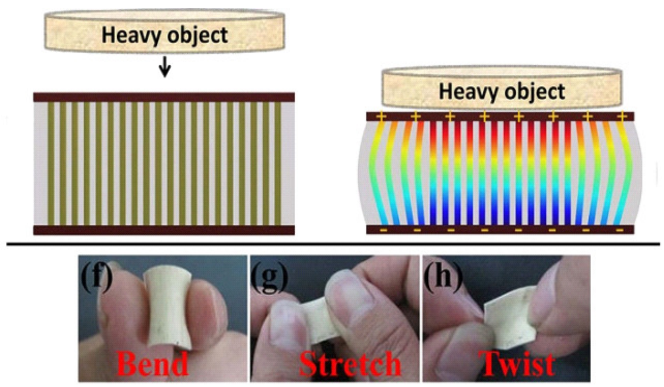

Fig. 2: Piezoelectric Material Properties

As discussed in the previous section as well in this section, it was seen that upcoming research trend is highly inclined on the use of piezoelectricity as energy harvesting method. One of the best parts of the piezoelectricity is that there is no upper limit of the energy availability (like thermoelectricity). As shown in Figure 2, the piezoelectric materials are highly flexible that can be bent, stretched, and twisted. However, the research challenges are more on how to manipulate such materials according to the necessary frequencies. Another research barrier is 'Goldilocks zone' [15] which is a type of ambient vibration that normally disrupts the efficiency of the piezoelectric materials. Although some research works [16] are found to use ceramic materials for the purpose of harvesting a wider bandwidth of surrounding vibrations, they also lack in flexibility. Hence, piezoelectricity and their possible ceramic alternatives for energy harvesting cannot be used for powering up mobile devices efficiently.

Fig.3: Bio-Mechanical Devices

The rise of biomedical devices is constantly up in futuristic research work. A study reported in [17] found that bio-mechanical energy harvesting techniques have the potential to generate a massive energy good enough to run multiple low-powered devices. However, the problem in this field is that majority of the devices are wearable and bulky, hence portability and mobility features pose a hindrance for generating energy. Apart from common physical activity (jogging, cycling, pushups etc), there is higher rate of inconvenience attributes associated with it. The biomedical devices could be possibly used for powering up mobile devices and other smaller computing devices to a large extent. However, the biggest obstacle factor in this research work is to come out with new light weight wearable devices and better storage capability for harvesting the energy.

Fig.4: Upcoming Solar Energy Harvesting

Solar energy harvesting for mobile devices is more than a decade old method. The upcoming trends in harvesting energy from sunlight are quite sophisticated. Figure 4 shows a cellular phone, where ongoing research work [18] is continued to charge up the battery from solar panel connected to the mobile phone. One of the research challenges in such futuristic solar energy harvesting is called as 'Shock let-Queisser' limit, which is a protocol that claims that a cell cannot harvest more than 30% of the solar energy that they capture. However, if the problem is seen in the viewpoint of the mobile phone, the research issues are generated from space and time complexities.

4. CURRENT RESEARCH CONTRIBUTION

The study towards energy harvesting evolves from more than a century by encompassing the conventional sources e.g. wind, water, sunlight, etc. With the rise of modernization, technology started contributing in this field and escalated the potential energy harvesting technology till date. Various available and frequently applied techniques in the existing systems include hydroelectric generator [19], wind turbines [20], and solar panels for the purpose of harvesting energy from the surrounding natural resources. One of the significant advantages of such energy harvesting techniques is virtual inexhaustible energy source with no harmful environmental effects. This paper focuses on finding the availability of free Radio Frequency (RF) energy to be used as a source of energy harvesting. The prime reason behind this is that there is a significant rise and modernization of communication system which lead to the increase of communicating devices that use RF as a medium of communication.

4.1 Significance of Current Systems

The research towards harnessing the existing RF sources dates only a decade old. The prime purpose of this exploration is to power up the low-powered devices from the ambient RF energy sources like signals captured from mobile phones or equivalent communicating devices. However, the existing RF levels are found to be very low compared to those provided by a dedicated RF level. Hence, it poses a significant research challenge in maximizing the efficiency of the energy harvesting system even for low-powered devices. Therefore, the majority of the researcher expressed that [21] the availability of RF energy is required to be measured in various locations. The studies also [22] suggest that integrating knowledge on RF energy harvesting along with emphasis on location of RF energy harvesters is an effective policy to maximize the performance of ambient RF energy harvesting. The archive of literature witness studies related to harnessing energy from television as well as from mobile phone base station.

Ahn [23] has performed research where he used 4*x*4 patch antenna using 2.13 GHz for low powered mobile devices. The author has used step-up converter with 0.7-5.5 Volt load, where the outcome of the study shows energy efficiency of 80.9%. The author has also successfully tested the application over ZigBee configured over a distance of 12m.

An extensive survey towards RF energy harvesting has also been reported by Pinuela et al. [24]. The authors have presented their investigation report on citywide RF spectrum identifying the precise locations and their potential impact on the service quality in energy harvesting technique. The authors have designed a Rectenna that was used for enhancing the efficiency of the energy harvesting technique. The authors have also presented detailed information about the multiband Rectenna array along with a discussion on *n* voltage summing and current summing for minimizing the input energy needed for harvester functionality. The authors have compared measured ambient RF energy harvesting mechanism with other types of non-conventional energy harvesting techniques. This study has put forward well the efforts to emphasize the need of harnessing the freely available of RF energy sources.

Similar research attempt in the same direction but in extremely unique way was seen in the study of Kuo et al. [25]. The authors have discussed that a standard headset of iPhone can generate approximately 16mW of energy per channel, which can be used for energy harvesting. In this study, the authors have designed an interface with name *Hijack* that permits the mobile device (phone) to readily integrate with the external sensors using the energy delivery features of audio jack. The outcome of the study shows a bi-directional communication medium over a Manchester encoded serial stream that is found to be extremely cost effective. The study has also exhibited that their framework is capable enough to deliver 7.4 mW to a load with 47% efficiency.

The most significant study toward RF energy harvesting exclusively for powering up mobile phones was presented by Qutaiba [26]. The author has designed a buck-boost DC-DC converter for consistently supplying a voltage to the mobile phone. The author has also used Nokia 1100, the basic model, for investigating the energy charging characteristics, where the outcome shows draining cycles using only 3V constant DC supply. One of the significant outcomes of the study is that the presented charging circuit was considerably simplified yielding to maximized performance efficiency.

Various other research works have been presented that address the issues of RF energy harvesting phenomenon. Table 2 illustrates the problems being addressed, with techniques applied for harvesting RF energy and remarks on technique being studied explicitly.

Table 2: Most Recent Techniques of Energy Harvesting

#	Author	Problem	Technique Applied	Remarks
1	Din et al. (2012) [27]	RF energy harvesting **Source**: antenna	Design 7-stage voltage doubler circuit **Tool**: Multisim software	It addresses only low powered sensors
2	Lenin & Abarna (2014) [28]	RF energy harvesting **Source**: GSM cell tower	Designed 5-stage voltage multiplier circuit **Tool**: ADS Software	Method not bench marked
3	Zhang &Ganesan (2014) [29]	RF energy harvesting **Source**: back-scattered signal	Designed network stack Quark Net **Tool**: USRP software radio reader	Efficient energy harvesting for micro-powered devices only
4	Prasad (2014) [30]	Energy harvesting **Source**: Low-Voltage Piezoelectric	buck-boost interleaved converter circuit **Tool**: Not defined	Not targeted for present mobile devices
5	Chao et al. (2014)[31]	RF Energy harvesting **Source**: antenna	Designed Circular &Spiral Antenna Array Tool: ADS Software	Not targeted for present mobile devices
6	Testa & Zorzi (2014)[32]	Energy harvesting, unknown state of charge **Source**: Energy harvesting device (EHD)	Proposed optimization of EHD **Tool**: Not defined	Targeted for WSN mainly
7	Paul (2014)[33]	Thermoelectric Energy harvesting Source: thermal points	Thermodynamic efficiency	Not targeted for present mobile devices
8	Niyato et al. (2014)[34]	Opportunistic RF Energy harvesting **Source**: antenna	Optimal channel selection policy **Tool**: Not defined	Efficient harvesting for cognitive radio only, Not targeted for present mobile devices
9	Sonawane &Sapkal (2014)[35]	Wireless charging of sensors **Source**: antenna	Unlicensed ISM bands **Software**: ADS Software	Not targeted for present mobile devices
10	Pradhan et al.(2013)[36]	Electromagnetic Energy harvesting **Source**: Rectanna	Micro-strip Patch Antenna (MAP)	Along with merits, MAP has demerits too
11	Dyo et al. (2013)[37]	Energy harvesting **Source**: Medium wave broadcast signal	Ferrite rod antenna **Tool**: Matlab	Method not bench-marked
12	Archer (2013)[38]	Energy harvesting	Designed a tool called 'Ekho' **Tool**: Embedded C, XMEGA µController	Method not bench-marked
13	Ortiz et al.(2013)[39]	Energy generation **Source**: mechanic vibration	Piezoelectric energy harvesting **Tool**: hardware based	Targeted for railway and aeronautical application
14	Alleyne (2013)[40]	Energy harvesting **Source**: Piezoelectric materials	Silver implanted aluminum nitride **Tool**: TRIM/TRIDYN	Not targeted for present mobile devices
15	Daud et al. (2014)[41]	Internal charging of battery **Source**: Circuit design optimization	New circuit design **Tool**: hardware based	Targeted for ZigBee

#	Author	Problem	Technique Applied	Remarks
16	Olivio et al.(2011)[42]	Energy harvesting **Source**: kinetic, thermoelectric, cell etc.	Remote powering **Tool**: Agilent Momentum	Targeted for sensors only.
17	Bouchouicha et al. (2010)[43]	Ambient RF energy harvesting **Source**: RF Broadcasting station	Optimized antenna array to increase RF input power **Tool**: ADS Software	Not targeted for present mobile devices, Method not bench marked
18	Cheung (2012)[44]	RF Energy harvesting **Source**: Rectenna	Transparent Rectenna array	Not targeted for present mobile devices.
19	Clememntino (2013)[45]	Energy harvesting **Source**: Piezoelectric materials	Single degree of freedom model **Tool**: commercial EH301A module	Not targeted for present mobile devices.
20	Wu &Lee (2012)[46]	Energy harvesting **Source**: Vibration	Piezoelectric MEMS Power Generators **Tool**: Hardware based	Not targeted for present mobile devices.
21	Filip et al. (2012)[47]	Energy harvesting **Source**: Sound	Electromagnetic transducer **Tool**: Hardware based	Not targeted for present mobile devices.
22	Reddy (2011)[48]	Energy harvesting **Source**: ambient vibrations and RF electromagnetic waves.	New power electronic circuits using antenna and piezoelectric generator **Tool**: P Spice	Ambient sources not considered &method not bench-marked.

It has been observed that from the year 2011 to 2014, there has been introduction of exclusive techniques that address the issues of RF energy harvesting. The research gaps explored from the studies are as follows:

- There is very little work is being explored for addressing RF energy harvesting exclusively for mobile devices; majority of the studies are more or less concentrated on low powered device like sensors. Studies towards powering up mobile phones are few to find.
- The studies presented by Reddy et al. [48], Bouchouicha et al. [43], Dyo et al. [37], and Lenin & Abarna [28] etc address the issues of energy harvesting using various techniques; however, none of the techniques was found to be efficiently being bench marked which cause a bit of uncertainty in adopting such frameworks for future usage.

We strongly believe that there are enormous potential in harnessing the RF energy for the mobile devices, which will open various avenues in non-conventional energy harvesting. Addressing the issues for other low powered devices like ZigBee, sensors are completely different compared to powering up mobile phones and upcoming mobile computing devices. Hence, a potential research gap is identified for not considering RF energy harvesting for mobile phones exclusively.

5. RESEARCH SCOPE

Harvesting RF energy has an extensive variety of examination. While the logical investigation of energy conversion standards are unquestionable for quite some time, still their provision stayed limited to constrained spaces in industry and overwhelming business. The nature is encompassed by energy in the form of vibration, wave, sound, water, heat etc. The advancement of new era technology for energy preservation has the potential as well as capability to convert environmental energy into electrical energy. Energy harvesting is a mechanism which enables the remote devices run for extended periods without getting them charged. The availability of free energy is the prime target of energy harvesting mechanism. Additionally, energy harvesting technique is utilized as an alternative source of energy for supplying an essential energy source for low powered devices. At present, such types of energy are trapped from sun, wind, water, electromagnetic energy, and thermal energy for the purpose of harvesting energy. Preserving energy for low-powered devices like remote sensors exhibits another challenge as the energy harvesting tool in the present era find it difficult for miniaturization as well as resource (battery) constraint nature of such sensors. Currently, the circuitry design of the sensors are not meant for storing energy gathered from external resources (Ambient Energy) due to resource limitations. In the following continuation of this discussion, the overview report of BCC (Business Communications Company, Inc.) examination is indicated in Figure 5.

This report synopses figure of worldwide business sector interest for vitality collectors by land district, 2010-2017($ millions) [49]. The global energy harvesting market was valued at $323 million in 2011 and should reach $514 million in 2012. Total market value is expected to reach nearly $3.1 billion in 2017 after increasing at a five-year compound annual growth rate (CAGR) of 43.2%.

- The Americas are expected to have a value of $253 million in 2012 and $1.4 billion in 2017, a CAGR of 40.8%.
- As a segment, EMEA (Europe, the Middle East and Africa) should total $113 million in 2012 and $670 million in 2017, a CAGR of 42.8%.

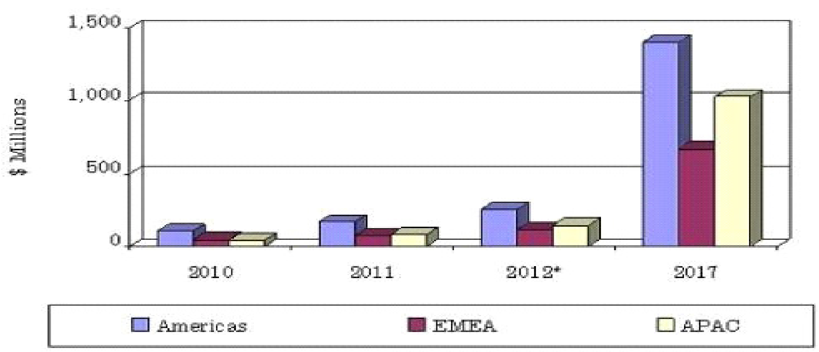

Fig. 5: Summary figure of global market for energy harvesters

The above report presents the forecasts for energy harvesters for 2012 through 2017 on a volume and value basis. The statistics show the sales values are presented in U.S. dollars, while shipment volumes are presented in thousand units. The energy harvesting used to power the wireless sensor nodes experience tremendous growth as well. This shows that there is tremendous scope for the research in the following energy sources:

- Solar and photovoltaic.
- Thermal.
- Vibration, displacement and mechanical
- Bio mechanical and electrostatic
- Radiation and electromagnetic.
- Chemical.

Hence, there is huge scope of using RF energy harvesting for mobile phones. Understanding the increment in utility of 3G-4G data connectivity and cloud services, majority of the computing devices are turning up mobile posing higher technical adoption of mobile phones and availability of free RF signals.

6. CONCLUSION

With the increasing use of mobile and computing devices, the problem of energy (battery) consumption is a rising issue. Such computing devices are of two types: (i) the first type which is always within the reach of external power (laptop) and second type which are not always within the reach of external power (mobile phone, sensors etc). Hence, there are possible situations in which second type of products are in need of energy for making the product operational under adverse conditions. This challenging situation requiring instant and immediate energy in adverse environmental condition gives rise to evolution of the research topic termed as energy harvesting, which is the core discussion of this paper. The paper discussed that energy can be captured from nature in various forms, e.g. heat, wave, water, motion etc. Various evidences of ongoing research and product availability have been jotted in this paper for visualizing the current trends of research direction in energy harvesting. However, one of the significant challenge that has been observed is, although the energy can be trapped from ambient resources, it is quite difficult to store and process it for some of the low powered devices like sensors as they have high degree of hardware and resource constraints. Finally, the paper has reviewed some of the most recent studies done in the last 5 years and discussed the research gap and found that work towards energy harvesting for mobile devices is very little to find. Hence, our future work direction will be to formulate a novel framework that could fill up the gap explored in this study.

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