OBNOVLJIVI IZVORI ENERGIJE U BEŽIČNIM SENZORSKIM MREŽAMA

RENEWABLE ENERGY SOURCES IN WIRELESS SENSOR NETWORKS

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Razvoj jeftinih mikroelektronskih komponenti niske potrošnje uslovio je ekspanziju bežičnih tehnologija u zadnje dve dekade. Jedna od glavnih mana svih bežičnih uređaja, uključujući senzorske, jesu ograničeni energetski resursi. U ovom radu opisani su uobičajeni mehanizmi koji se koriste u „energy harvesting" i „energy scavenging" procedurama, kojima se snaga iz okoline koristi za dopunjavanje energetskih rezervi u bežičnim senzorskim mrežama. Oni uključuju konverziju energije elektromagnetskih talasa, vibracija i toplote.

Ključne reči: *energy harvesting; bežične senzorske mreže; mikrogeneratori; nanogeneratori; solarna energija; termoelektricitet; piezoelektricitet; piroelektricitet; triboelektricitet*

The advances in the technology of cheap and low power consumption microelectronic components have lead to the expansion of wireless technologies in the past two decades. One of the most important shortcomings of all wireless devices, including sensor ones, are limited energy resources. This paper reviews common mechanism of energy harvesting and energy scavenging, which draw power from the environment to feed the energy reserves in wireless sensor networks. They include conversion of the energy of electromagnetic waves, vibrations and heat.

Key words: *energy harvesting; wireless sensor networks; microgenerators; nanogenerators; solar energy; thermoelectricity; piezoelectricity; pyroelectricity; triboelectricity*

1 Introduction

It has already been over two decades since advances in microelectronics lead to the expansion of wireless technologies. Wireless sensor network (WSN) has several distinct advantages over a wired one. The cost of cabling material and labour is eliminated and the sensor nodes are more mobile and more easily attached at hard-to-reach locations. However, WSNs also have disadvantages limiting their use in many fields of application. They include lower data transfer speed and sensibility to interferences of all kinds, natural and human induced, including security issues (attacks by malicious users). One of the major shortcomings of all wireless devices is limited energy supply. The devices, especially the sensing ones, are often placed on remote spots so that regular replacement of batteries is not feasible, and additional energy sources must be provided.

The process of energy gathering is commonly referred to as "energy harvesting", whereas the phrase "energy scavenging" is also used. The difference between the two terms is that harvesting is a process of obtaining energy from environmental (mostly, but not necessarily natural) sources which are expected to be periodically or continually present (such as the solar or wind power), whereas the scavenging refers to rare and sporadic events incorporating (mostly, but not necessarily artificially) generated energy, already used for other purposes, such as a burst of electromagnetic waves, mechanical vibrations caused by passing objects, etc.

The following three energy sources are most frequently used in the wireless sensor networks: light, vibrations and temperature gradient. Solar cells can provide satisfactory energy input for most outdoors applications. For applications on locations which exhibit frequent vibrations (such as civil engineering structures with heavy traffic load) or human bodies in motion, piezoelectric and induction based microgenerators are practical solutions. Temperature variations may also be utilized, when appropriate, by generators such as those based on the thermoelectric effect.

This paper presents a short review of the mentioned energy harvesting and scavenging methods used in or designed for contemporary wireless sensor networks. Some of the mentioned solutions are at the prototype level, and their usefulness in commercial applications is yet to be put to the test.

2 Minimization of energy consumption in WSNs

WSNs are composed of a number (which may vary from several to thousands) of sensor devices (nodes) monitoring some physical phenomena and communicating with each other by the means of electromagnetic waves (almost exclusively in the radio frequency domain). A typical sensor node is comprised of four basic elements: a power supply module (which may include an energy harvesting mechanism), a CPU board, a sensing part, and a communication module. Modular design strategy in terms of possibility to use different sensors and radio modules is often employed. A sample wireless sensor device suitable for IoT (internet of things) applications with open source software support (SDK and API), Waspmote [1], is shown in Fig. 1. Competing brands include TelosB, MicaZ, Mica2, WiSense, Imote, etc. [2].

More complex networks are usually divided into clusters, and the main station (hub) of the network, usually a personal computer, communicates with the cluster heads (central nodes of clusters), sometimes called gateways or sinks, which gather the data locally (act as loggers). An example of topology of such a network (a simple one, for illustration purposes) is presented in Fig. 2.

Fig. 1. Waspmote, an open-source platform node

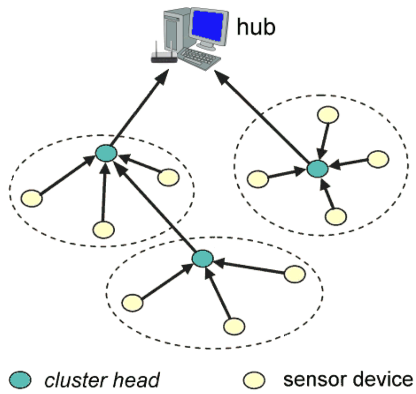

Fig. 2. Clustered network topology example

A number of MEMS and other sensors have been developed in the recent past, with very low power consumption, so the process of measurement, as well as local data processing on low consumption CPUs, does not present the primary challenge in energy conservation. It is the process of communication - the constant exchange of data packets - that consumes most energy here. Radio modems or transducers usually draw currents in the order of 10 mA or more (equivalent to tens or hundreds of mW) during the active communication. The exact number is largely dependent on the required range. Higher the range, higher the power demand.

Main strategies employed to minimize energy consumption are entering the sleep mode (for both main electronics and the communication module) as often as possible and clever use of the radio interface. The latter often incorporates complex operations in the network topology configuration. Messages are relayed instead of being sent high distance. The data flow is carefully optimized for each application according to its measurement task. Sometimes, the data is processed by the onboard DSP unit and only the results (conclusions), not raw measurement data, are transmitted. Also, the sensor nodes may use logic to differentiate between important and non-important events and decide when the data transfer is in order.

Nodes usually take note of their own battery energy level and refuse to participate in data exchange (keep the radio module shut down) in case it is below a predefined critical level, because regular CPU operation could be jeopardized.

3 Electromagnetic waves harvesting in WSNs

Most common mechanism for electromagnetic waves harvesting is photovoltaic effect, employed in solar cells. Sun provides us with abundant energy that basically powers everything on Earth. Solar energy is an attractive sustainable option for many applications due to its renewability and wide mobile accessibility. The only requirement is that the devices are placed so that they are exposed to sufficient illumination. Artificial lighting sources can also be used when appropriate. The second method, less frequently used, is harvesting by rectennas, which can be feasibly performed in the radio and microwave part of the electromagnetic spectrum.

3.1 Solar cells

Photovoltaic effect in the semiconductor solar cells happens when incident photons excite electrons out of their bound states, thus creating new electron-hole pairs in the p-n junction. Electrons and holes are then pulled to different sides by the intrinsic electric field, thus creating the electric current if a load is connected.

Solar cells, grouped in solar panels, are very commonly used to power wireless nodes. Most solar cells today are made of monocrystalline or polycrystalline silicon, which is natural since the silicon is one of the most abundant elements on Earth. Sun can provide over 1 kW/m^2 raw power, which can be transferred to electric energy with variable efficiency coefficient, which used to be around 10% in the earlier days, but has reached over 20% for modern date commercial products, and can go over 30% [3]. Additional losses occur in the circuitry which transfers the energy from the cells to the rechargeable batteries powering the main board. This circuitry often contains intermediate supercapacitors serving as primary energy storage (downside of this approach is that supercapacitors require a lot of volume which is in contrast with miniaturization demand). Some wireless nodes operate without batteries (they are *batteryless*), only using the supercapacitors. This applies to other types of energy harvesters too.

Outdoor solar panels yield about 10 mW/cm^2 net power, whereas indoor variations are typically limited to about thousand times less amount (about 10 μW/cm^2) [4].

Tab. 1. Characteristics of some solar modules used in WSNs

node	*solar cell/panel or harv. module*	*size* [cm^2]	U_{mp}[V]	I_{mp}[mA]	P_{max}[mW]
HydroWatch [5]	Silicon Solar 16530	5.84×5.84	3.1	89	276
Everlast [6]	Solar Made SPE-50-6	9.52×5.7	6	75	450
Solar Biscuit [7]	a cell by Shell Solar	5×5	5	20	100
Tmote Sky [8]	a string of CPC1824	112	4	12.5	50
Prometheus [9]	Panasonic Sunceram BR-378234C	8.2×3.7	3.4	40	136
Tempo [10]	eZ430-RF2500-SEH	5.7×5.7	3.5	0.1	0.35
MicaZ [11]	Solar World 4-4.0-100	9.52×6.35	3.2	2	6.4

Parameters of some SEH-WSN (solar energy harvesting wireless sensor nodes) described in the literature are given in Tab. 1. All mentioned cells are silicon, mostly monocrystalline. U_{mp} and I_{mp} denote maximum power point (MPP) voltage and current for the respective panel. The figures in the table are given for typical working conditions in a given application (they are not maximum in the sense of maximized solar irradiance). They depend on a number of variables, but mainly the incident power and the temperature. A maximum power point tracking (MPPT) circuit is often engaged to adjust the load impedance and provide maximum energy transfer from the solar panel.

Powers in [10] and [11] are the lowest because the operation was performed indoors, in the latter case in a close proximity (1 cm) of a fluorescent tube.

Thin films of perovskite materials (which will be described shortly in 5.2) with protective coatings seem like a promising successor to the silicon, due to low cost and solid efficiency. Until recently, they have proven too fragile, but latest technological advances in this area are improving this issue [12]. They might replace the silicon soon; or, at least, team up with it, in the recently developed *tandem* solar cells [13].

3.2 Rectennas

Rectennas (antennas that harvest electric energy from the incident electromagnetic waves, and come in many shapes and sizes; a sample rectenna is shown in Fig. 4) may come handy if there is a need to harvest energy at nodes which operate either at night or in dark spots, but with access to sufficient intensity radio or microwave electromagnetic waves. Due to lower energy density of these waves, rectennas cannot power nodes with high energy demands, except in case energy is being transmitted especially for this purpose. Although advances in nanotechnology did enable the construction of infrared and visible spectrum rectennas (nano-antennas or nantennas), this technology does not promise commercial viability in the near future [14].

There were a number of successful rectenna deployments in the area of WSN; however, they were primarily prototypes, rather than the most convenient options chosen for feasible harvesting in specific cases. Several examples will be described.

Nishimoto et al. [15] showed that UHF rectennas can harvest as much as 20 mW of power from the television signals emitted from Tokyo Tower, 6 km away. However, UHF tv is being phased out throughout the world, and the output power level of mobile telephony base stations, AM radio stations, local wi-fi routers, mobile phones, and other devices producing environment radio energy today, is several orders of magnitude lower. Power densities from these sources in urban areas are typically under 0.1 $\mu W/cm^2$ [16].

Assimonis et al. [17] employed low-cost rectenna based harvesters with batteryless backscattering wireless sensor nodes, exposed to 0.07 $\mu W/cm^2$ or less. Backscatter communication is a method in which input signal provides energy for the receiver, which functions in a manner similar to a passive RFID: the signal is reflected with additional information embedded into it. This promising technology still has major limitations. The communication range is limited, the speed (data transfer rate) is very low, and sensor's susceptibility to electromagnetic interferences grows with its ever-lowering power consumption (which may be of special interest in industrial environments).

Loubet et al. [18] deployed broadband rectennas (868-915 MHz) with batteryless wireless sensor nodes performing humidity and temperature readings (intended for use in structural health monitoring) once every two hours under 0.5 $\mu W/cm^2$ input power density. They used cheap rather than ultra-low consumption sensors and argue that measurements may be performed with the daily frequency using the latter, thus making their system capable of self-sustaining under much lower input power circumstances (which would be a more realistic scenario).

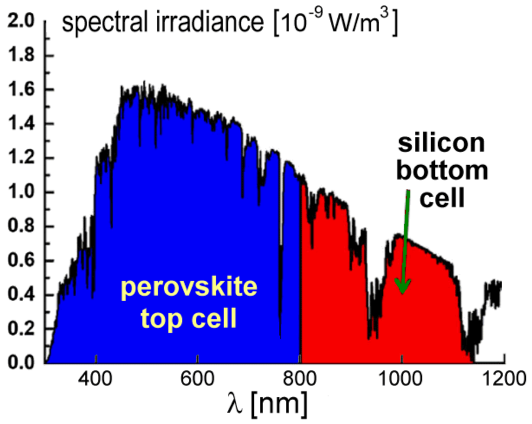

Fig. 3. Prv-Si tandem cell spectral response [13]

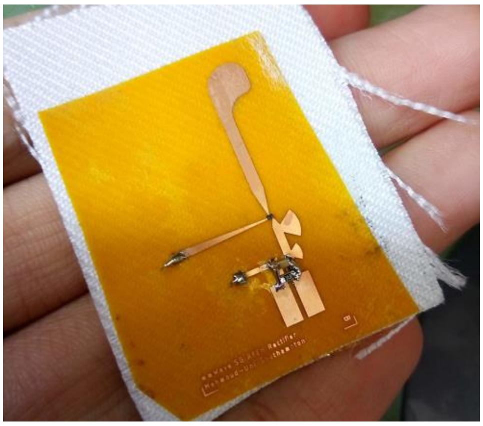

Fig. 4. Rectenna harvesting λ=1mm waves

4 Mechanical energy harvesting in WSNs

Mechanical energy is harvested in WSNs applied either in civil engineering structures, machines and vehicles exposed to vibrations, or in case medical sensors are attached to human body. Two most common methods for mechanical energy conversion used in WSNs are piezoelectricity and electromagnetic induction (microgenerators). Electrostatic energy harvesters are also used, which work on the principle of applying mechanical pressure to increase electrostatic energy contained in a capacitor by changing its geometry (surface area and the distance between the plates may be altered). Finally, triboelectric harvesters are a promising emerging technology. They operate on the principle of electrification by friction. In the recent years, there are also a growing number of hybrid harvester designs, which make use of more than one of the mentioned mechanisms [19].

4.1 Piezoelectric energy harvesters

Piezoelectric harvesting is popular in recent WSN developments due to its relatively high efficiency and miniaturization potential. Piezoelectricity is a phenomenon of interdependence between mechanical pressure and electric polarization, occurring in some crystals where centres of positive and negative charge inside a lattice element drift apart as a function of mechanical stress. Best known piezoelectric material is quartz. Although quartz is both abundant and often used for its other traits, such as resonant frequency stability, energy harvesters use other materials because of their higher piezoelectric constants (they produce more electric charge than quartz when exposed to the same pressure). Zinc oxide (ZnO) and aluminium nitride (AlN) are especially suitable for use in MEMS technology, whereas lead zirconate titanate (PZT) is a ceramic material often used due to its high constants. New and promising materials PMN-PT and PZN-PT (lead magnesium/zinc niobate - lead titanate) feature even higher piezoelectric constants [20].

Tab. 2. Characteristics of some PEH (piezoelectric energy harvesters) designed for use in WSNs

developed by	*size*	*material*	*excitation*	*f* [Hz]	*power*
S.P. Matova et al. [21]	< 1 cm^2	AlN	*v*=13 m/s*	309	2 μW
S.S. Balpande et al. [22]	78 mm^2	ZnO	1g	90	5.75 μW
G.T. Hwang et al. [23]	3×4 cm^2	PZT	manual	1.7	200 μW
E.K. Reilley et al. [24]	*L* = 3 cm (trapez.)	PZT	1g	100	45 mW
J. Lee & B. Choi [25]	60×10×0.3 mm^3	PZT	*v*=60 km/h**	variable	380 μJ/rev.
G. Ferin et al. [26]	6×30×5 mm^3	PZT	0.1g	23.2	60 μW
B. Dziadak et al. [27]	*d* = 2.7 cm (×2)	PZT	0.6-4 m/s^2	4-10	60 μW
A. Mouapi [20]	53.5×27.6 mm^2	PMN-PT	0.11g	22	120.7 μW

Basic design adopted by most researchers by far seems to be the cantilever. One or two layers of piezoelectric material are applied (on opposite sides, if there are two) on the elastic substrate of the cantilever. Unimorph (one layer, as opposed to bimorph) arrangement is illustrated in Fig. 5, showing two basic *coupling modes* (d31 and d33). Originally, d_{em} denotes the value of piezoelectric constant for output electric polarization in the direction of *e* with input mechanical excitation in the direction of *m*, and the coupling modes are labelled accordingly. In both cases from Fig. 5, vibrations on the free end, where seismic mass is added optionally, cause stretching along the length of the cantilever, so mechanical excitation is longitudinal, and electrical polarization is either transversal (vertical) in d31 case or longitudinal in d33 case (where positively and negatively charged regions repeat with a certain wavelength).

Parameters of some harvesters of this type, realized in the near past, are given in Tab. 2.

4.2 Electromagnetic induction microgenerators

Electromagnetic induction microgenerators contain either a moving coil or a moving magnet, so they turn magnetic flux variations into electric current according to the Faraday's law. Microgenerators (also referred to as EMEH - electromagnetic energy harvesters) are in wide use despite of their numerous disadvantages: problems with further miniaturization, moving parts being prone

* vibrations were induced from the air flow inside a Helmholtz resonator
** the PEH was attached to a car wheel, and the energy is given per revolution [μJ/rev.]

to malfunction, low voltage and efficiency problems at lower frequencies. Neodymium (NdFeB) is the most popular material used as the magnet in EMEH due to its strong field and resilience to vibrations induced demagnetization.

Two basic types of microgenerators are oscillatory (translational) and rotational. Hybrid generators are also often realized using some sort of a mechanism to convert (chaotic direction in some cases) linear motion into rotation. While oscillatory generators are easier to construct, the limited displacement of the moving part makes them unable to produce larger powers, especially at lower excitation frequencies. Rotational and hybrid EMEH may pose more engineering challenges, but are generally more efficient.

Parameters of some microgenerators realized in the near past are presented in Tab. 3.

Tab. 3. Characteristics of some electromagnetic induction microgenerators designed for WSN use

developed by	*size*	*excitation*	*type*	f [Hz]	P_{max} [μW]
S.P. Beeby et al. [28]	0.1 cm^3	0.59 m/s^2	oscillatory	562	46
W. Zhang et al. [29]	17.1×16.2 mm^2	not specified	oscillatory	18	423
F. Orfei et al. [30]	15×15×20 mm^3	bridge vibrations	oscillatory	8	26
S. Bakhtiar et al. [31]	24.73 cm^3	fluid, v=18m/s	oscillatory	107	18600
M.A. Halim et al. [32]	L = 4.2 cm	human body	oscillatory	5	2150
Niroomand & Foroughi [33]	d = 5 cm	human body	rotational	<10	416.6
H. Liu et al. [34]	33.1 cm^3	human body	rotational	8	10400

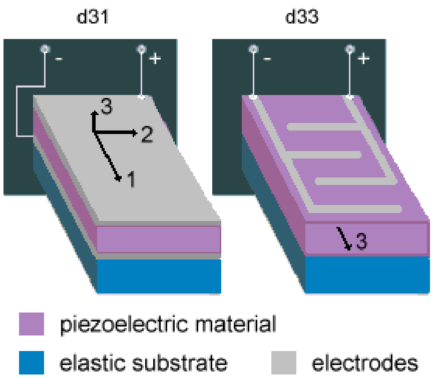

Fig. 5. Unimorph cantilever modes

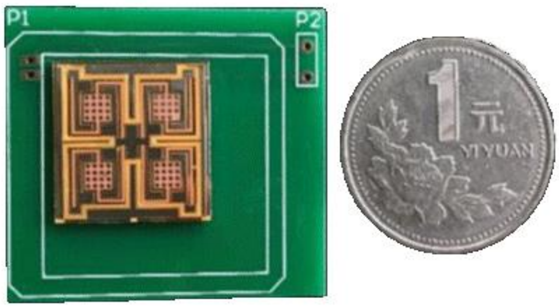

Fig. 6. MEMS microgenerator developed in [29]

4.3 Electrostatic energy harvesters

Electrostatic energy harvesters (EEH) principle of operation is boosting electrostatic energy contained within a capacitor exposed to geometry variations by increasing either its voltage or charge. EEHs typically produce less power than piezoelectric and electromagnetic harvesters. There are two basic kinds of EEHs. Electret-free harvesters have conversion cycles, which requires an active electric circuit to be synchronized with the mechanical excitation in order to maintain the operation. Electret-based harvesters, on the other hand, involve the use of (quasi)permanent electrically polarized materials (the word *electret* is derived from *electricity magnet*).

Many types of cycles are possible with variable geometry capacitors, very similar to thermal cycling machines. One of the simplest and most often used cycles in electret-free harvesters is the charge-constrained cycle. First, the capacitor is charged to the maximum capacitance state (U_{min}, C_{max}) using a circuit powered by energy already present in the harvester. The capacitor is then disconnected and the geometry is changed until maximum voltage state is reached (U_{max}, C_{min}). External mechanical energy is converted to electric potential energy during this process, while the charge $q=CU$ remains constant. Finally, the charges are removed (the capacitor is emptied), gaining more electrical energy than it was invested in the first step.

Capacitors with electret layers can be represented as a serial connection between a capacitor and a voltage source. If we close the circuit with a load and start altering the capacitor geometry/capacity, electric current starts flowing, as voltages tend to equalize.

Examples of realized electrostatic harvesters are presented in Tab. 4. We see that the highest powers are obtained from the turbines powered by fluid flow [37], and the same applies for other mechanical energy harvesters as well ([31] in Tab. 3). This is due to greater incident power density than in case of environment and human body vibrations, and not related to the conversion mechanism itself.

Tab. 4. Characteristics of some electrostatic energy harvesters (EEH) designed for WSNs

developed by	*size*	*electret*	*excitation*	f [Hz]	P_{max} [μW]
H. Takhedmit et al. [35]	d = 10 cm	no	1.5g	25	0.4
P. Basset et al. [36]	66 mm^2	no	0.25g	250	0.061
M. Perez et al. [37]	12.6 cm^3	yes	10 m/s wind	10	1800
Y. Zhang et al. [38]	1.3×1.8×0.15 cm^3	yes	26.93 m/s^2	142	30
C. Gao et al. [39]	L = 63 mm	yes	5 m/s^2	74	404

A diagram of a comb capacitor (often used in MEMS electret-free EEH) with a variable gap is given in Fig. 7. Note that if the movement direction changes orientation by 90°, we get a comb capacitor with a variable surface. Similar designs are employed in MEMS technology not only in energy harvesting, but in sensing as well. It is very common for capacitive MEMS accelerometers to use this setup.

4.4 Triboelectric energy harvesters

Triboelectric (friction based) devices are becoming more popular in the recent years, as their low cost makes them a promising future research subject. Most of them are miniature, and are often referred to as TENG (triboelectric nanogenerators). The design of a basic triboelectric harvester is simple: just apply an appropriate material to the electrodes, let mechanical excitation cause the friction, and harvest the charge (current). Materials used at this moment are diverse, but dielectric polymers seem to be gaining popularity [40].

Friction powered LED array from Georgia Institute of Technology [41] is presented in Fig. 8. Several realized triboelectric energy harvesters will be described in this paragraph.

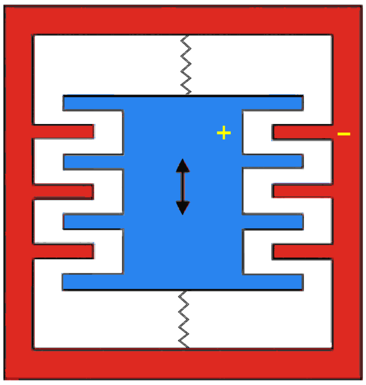

Fig. 7. A comb capacitor in EEH

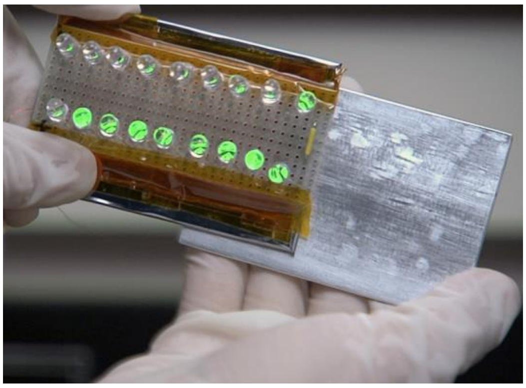

Fig. 8. Triboelectricity powering a LED array [41]

Kim et al. [42] used thin films of polydimethylsiloxane (PDMS) and aluminium to create a nanogenerator whose efficiency was improved by using a classical gear train. It was shown that at low excitation frequencies, in the order of a Hz, increasing the frequency applied to the actual generator by a factor of up to 5 using the gears produces a significant increase in the power generated, and power density (power per capacitor surface) over 6 W/m^2 was reached. At higher frequencies, this is no longer true, due to mechanical and other losses, so it was shown that gears are a suitable tool to optimize the nanogenerator's working frequency.

Wu et al. [43] tested a prototype hybrid electrostatic-triboelectric (E-TriG) generator. Both effects occur on the same capacitors. They tested several different electret materials with aluminium electrodes. It was shown that in order for the effects to add up (charges to be synchronized), negatively pre-charged electret must be used. Corona charging at ±6 kV was used to add quasi-permanent positive or negative charge to the electret material. The generator was placed inside an airflow tube. A flapping wing acted as a common electrode for two surrounding capacitors (6.7×2.2 cm^2). The power obtained peaked at 400 μW.

Xu et al. [44] developed a buoy with stacked triboelectric generators to harvest the waves energy. Each generator contains twenty polytetrafluoroethylene (PTFE) balls moving freely across an arc surface. This design enables the generator to better respond to excitation in directions other than the one favoured by the position of electrodes. Due to friction, balls get charged, and start inducing opposite sign charge on the electrode placed below the arc surface (which is coated with nylon) on the side they sway to (the same sign charge appears on the farther electrode to compensate as the current flows between). Obtained power density from a buoy was 10.6 W/m^3. Wang et al. [45] used a similar design to stack even more “sandwich-like” nanogenerators (S-TENG) into a self-powered buoy for navigation, reaching 34.65 W/m^3.

5 Thermal energy harvesting in WSNs

Two established thermal energy harvesting mechanisms are Seebeck effect and pyroelectric effect. In order to harvest thermal energy from the environment, there must exist a temperature difference, either between two points in space (for the Seebeck effect) or two points in time (for the pyroelectric effect). Thermomagnetic harvesters, which gained popularity recently due to advances in technology of materials with Curie temperature close to room temperature, are another option.

5.1 Thermoelectric generators

Although this type of thermal energy harvesting is not as efficient as some others, simplicity of installation and maintenance (lack of moving parts), along with environment friendliness, makes it a viable choice for many applications.

Hot end of a metal or semiconductor wire generates electron-hole pairs faster than the cold one. Majority charge carriers spread faster through the entire volume, causing the voltage to appear between two ends (hot end is positively charged in case of metals and n-type semiconductors). This is called Seebeck effect. In order to harvest the voltage, a thermocouple must be used, which is a pair of wires made from different materials, connected at one or both ends. Voltage per temperature difference (minus Seebeck coefficient) depends on the material (as well as other parameters), so end-to-end voltages of two wires, exposed to the same Δt, are different by default. If we connect them at one end, junction potentials equalize, and the voltage occurs between the free ends. Now it can either be monitored for sensing, or a load can be connected to harvest the energy. Connecting both ends is essentially the same, as a current now starts flowing (RI compensates the electromotive force in a closed circuit), and it may be measured or harvested serially.

Tab. 5. Characteristics of some thermoelectric generators (TEG) designed for use in WSNs

thermogenerator type	*size*	Δt [°C]	P_{max} [mW]
4 custom BiTe thermopiles [46]	$8 \times 8.2 \times 6.7$ mm^3	body-room	0.18
F40550 Xinghe Electronics [47]	4×4 cm^2	15	>0.084
127 custom Bi_2Te_3 thermocouples [48]	5×6 cm^2	80	3.12
CP85438 Cui Devices [49]	278 mm^2	10.5	2.5
6 Bi_2Te_3-Sb_2Te_3 thermocouples, radial [50]	L=1cm, d_{out}=4.5cm	5.9	2.3
two GM-200-127-14-16 [51]	$(2\cdot)40 \times 40 \times 3.6$ mm^3	180	13.1
SP1848-27145, Bi_2Te_3 [52]	$40 \times 40 \times 3.4$ mm^3	30	32

Voltage output of a single thermocouple is small, so a large number of them are connected serially to obtain *thermopiles*. Thermoelectric generators (TEG) are composed of one or multiple thermopiles (which are usually connected in parallel). Materials employed at moderate temperatures ($t < 200$ °C) are mostly semiconductor based (Bi_2Te_3, Sb_2Te_3, SiGe, etc). Ideally, they are characterized by high Seebeck coefficient combined with good electric and poor thermal conductivity. Other desirable traits are low variations of these parameters in a wide temperature range and mechanical robustness. P and n-type variations of the same materials are often coupled.

Tab. 5 lists some parameters from the literature. A downside of the thermoelectric method is that dimensions given in the table do not include the bulky heat sinks, usually employed in the process. Note that powers are higher than of some harvesters mentioned in previous paragraphs, not due to better efficiency, but because of the fact that thermal energy density is typically higher than that of light or vibrations.

5.2 Pyroelectric generators

Pyroelectric effect occurs in some crystals when their temperature changes in time. Temperature variation in the material alters the crystal spatial structure. Redistribution of ions creates voltage across the material, in a manner similar to piezoelectric effect. This polarization is not permanent, and fades out with leakage, after the cooling or heating is stopped. All pyroelectric materials are piezoelectric, but some piezoelectric materials are not pyroelectric. Ferroelectricity (present in many electrets) is also connected to pyroelectricity. Pyroelectric effect is also useful in sensing temperature fluctuations.

A variety of materials, in monocrystalline, film, bulk ceramic, polymer composite, etc. form have been used, some of them already mentioned in 4.1 (piezoelectric energy harvesters), but lead-free perovskite type ferroelectric ceramics seem to be on the rise, due to mechanical stability (resilience to humidity, temperature variations, vacuum, etc), low cost, and high reliability. Perovskite type materials (perovskite structures) are also significant in contemporary solar cells design. They feature intertwined cube and diamond-alike crystal lattice elements, with the general chemical formula ABX_3. This is illustrated in Fig. 9, where blue dots represent A, red dot represents B, and green dots represent X atoms (ions) or their groups.

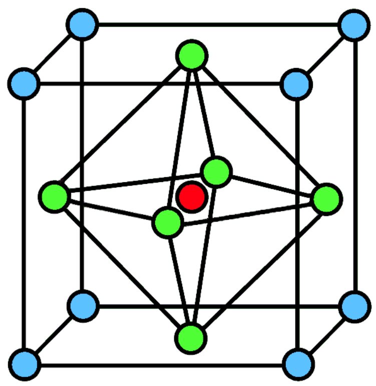

Fig. 9. Perovskite crystal structure

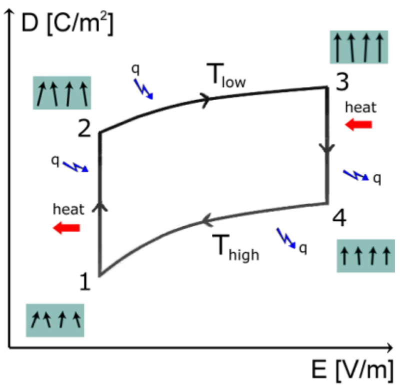

Fig. 10. Olsen cycle in a PyEH

Efficiency of pyroelectric harvesters is better than of their thermoelectric counterparts, and they do not require heat sinks which use up a lot of volume, but they are not always practical because they require temporal temperature fluctuations. Heat pumps, like refrigerators and air conditioners, exhibit such fluctuations, so their waste energy can be conveniently harvested using PyEH (pyroelectric energy harvesters; sometimes PyNG or PENG for *nanogenerator*).

In a PyEH, pyroelectric material is placed between the electrodes of a capacitor. Varying charge on its surfaces causes variations in the charge of the electrodes, inducing the current which can be harvested. That is basically the same as in the electrostatic harvester described in 4.3, except that charge variations are of different origin. Pyroelectric harvesters operate in cycles too. There is a variety of cycles, but Olsen cycle [53] (illustrated in Fig. 10) is the most frequently used because of its high efficiency. During the 1-2 (isoelectric cooling) and 2-3 (isothermal charging) processes, electric energy is being invested in the system. Dipoles increase their electric moment and align better. During 3-4 (isoelectric heating) and 4-1 (isothermal discharge), exactly the opposite happens. Since 3-4-1 occurs at higher electric field intensity (same charge being exchanged as in 1-2-3), net electric energy is extracted from the system.

Not many dedicated wireless sensor networks have been employing pyroelectric harvesting, and some related work will be described shortly.

Yang et al. [54] constructed a PZT film based pyroelectric harvester which produced 0.215 mW of power for 45 K range changes with the speed of 0.2 K/s. This harvester powered a wireless node for temperature measurements, with 50 m radio range.

Hunter et al. [55] devised a MEMS poly(vinylidene fluoride-trifluoroethylene) (PVDF-TrFE) based pyroelectric capacitor connected to a cantilever (bimaterial strip) which periodically brings it in contact with hot and cold surfaces. This harvester is intended to power wireless nodes monitoring the nuclear plants. Calculations show that a 2D array of 60×170 MEMS harvesters could cover an area of 750 mm^2 and deliver 10 W of power if supplied with $\Delta T=150$ K. Increase in power compared to the previous designs is due to very fast oscillations of the cantilever (50 Hz).

Gusarov et al. [56] created a hybrid piezoelectric and pyroelectric harvester (not surprisingly, since the two effects are closely connected). TiNiCu shape memory alloy (SMA) was used to introduce heat induced strain, and polyvinylidene fluoride (PVDF) was chosen for the active material. This configuration achieved energy density of 0.41 mJ/cm^3 per one temperature variation of 20 °C magnitude. At 70 °C (maximum temperature for the SMA), four stacked elements were able to power a batteryless wireless node.

5.3 Thermomagnetic harvesters

Thermomagnetic generators employ the effect of ferromagnetic materials being heated over their Curie temperatures, at which they lose ferromagnetic properties and become paramagnetic. Change in the magnetic flux can be used to produce electric current in a coil wrapped around the material. One of the first designs of this type was reported by Nikola Tesla in the 19^{th} century [57], however, thermomagnetic generators did not attract much attention until recently, when gadolinium and its alloys came into focus, with Curie temperatures around the room temperature. A number of similar thermomagnetic devices, including motors (which convert heat to motion), have been proposed in the recent years [58].

Although few thermomagnetic harvesters applied in wireless sensor networks were documented, with generators already being realized in centimetre sizes [59][60], reports are most certainly expected soon.

6 Conclusion

Harvesting and scavenging the energy of electromagnetic waves, vibrations and heat shows the greatest potential in meeting the power needs of future rechargeable-battery-powered and batteryless wireless sensor devices and networks. Main physical mechanisms of energy conversion and harvesters' principles of operation were described. Several research challenges in progress and possible future development directions were addressed.

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