Energy Harvesting in Smart Cities

Zheng Jun Chew, Yang Kuang, Tingwen Ruan, and Meiling Zhu

Abstract Smart cities rely on a plethora of sensors at various locations in urban environments to collect data so that the living standard can be improved using the information gathered. Wired sensors that have limited flexibility and high installation costs are less attractive. Wireless solutions are flexible and low cost to install but their requirement of regular battery replacement introduces a high maintenance cost. By endowing wireless sensors with energy harvesting capabilities to harvest energy from the environment such that they can be energy self-sufficient, the maintenance cost associated with battery replacement can be eliminated, which is a more sustainable and environmentally friendly approach for the realisation of smart cities. This chapter reviews the core elements of an energy harvesting powered wireless sensor system, from the energy harvesters that harvest the energy to the power management circuits that convert the harvested energy into a form that is usable by the wireless sensors, and finally the wireless sensors that collect and transmit data. Kinetic energy is abundant in urban environments due to the dynamism in cities that comes from high human activities. Therefore, this chapter focuses on kinetic energy sources that are available in urban environments and their associated energy harvesters. For the power management circuit, particular attention will be on its key subsystems to achieve a high performance circuit. Finally, the features that make a wireless communication technology suitable for the applications of smart cities with the available energy sources will be reviewed with some example applications given.

1 Introduction

With an ever-increasing human population and the population shift from rural areas to cities, there is a critical need to ensure sustainability without compromising or even enhancing the living quality of the increasingly populated cities [1]. It is envisaged that this improvement in the city life can be achieved if the infrastructure and resources can be utilised more efficiently. Therefore, the concept of smart cities emerges where intelligence and connectivity are imbued in conventional cities for better city operations and management with the data gathered and information exchange by the city administrators. Such a transformation from ordinary cities to smart cities is very similar to incorporating wireless connection and other functionalities into conventional devices such as televisions, meters, watches and many more for better performances and user experiences, which awarded them the prefix of 'smart'. This means smart cities can be realised by leveraging and integrating technologies such as sensing technologies as well as information and communications technology (ICT), which requires extensive sensor networks to be deployed throughout the cities to empower the cities with the information gathering and exchanging capabilities [2].

The deployment of sensor networks over a city-wide area is not without any challenges. Mains power is readily available in urban environments, which means the most straightforward way would be to connect all the devices via cables. Installing cables all over the place to power all the sensors would have an adverse impact on the aesthetic of the cities. Embedding or cover up the cables is a possible way but this could be very costly to execute and disruptive to existing structures in the city where extensive digging, drilling and burying are required to lay the cables. Moreover, the sensors themselves are generally low cost, which makes the high installation cost unjustifiable. Therefore, wireless sensor networks become the undisputed choice to make the intelligence and communication of smart cities possible in areas beyond the reach of wired infrastructure due to the prohibitive costs and effort involved. While wireless solutions offer a plausible way for mass deployment of sensor networks, they come with a long-term sustainable issue that arises from the need for regularly locating the wireless sensors and replacing their batteries so that the wireless sensor networks can continue to operate. Such a long-term maintenance requirement is undesirable as it can be very labourious, and hence costly especially in remote areas such as underground or embedded structures. The vast amount of depleted batteries from all the wireless devices also require proper disposal or recycling to avoid environmental issues due to the leakage of contaminating chemicals from the batteries.

However, thanks to continuous innovation and progression in enabling technologies of wireless sensing devices such as communication protocols, semiconductor and new advanced materials that greatly reduce the power consumption of wireless systems, an alternative to batteries for powering the low power wireless devices is viable by using energy harvesting. Wireless devices with energy harvesting technologies could be energy self-sufficient by harnessing energy sources from their ambient environments to power themselves or recharge their batteries for extended operation than conventional battery-powered only devices. This will greatly reduce the maintenance requirement of wireless sensor networks and improve their sustainability for long-term deployment. This chapter will introduce some innovations in energy harvesting technologies that comprise of the energy harvesters, power management and wireless sensing and communications for smart city applications.

2 Kinetic Energy Harvesting in Urban Environments

Abundant sources of energy present in urban environments, which include solar energy, thermal energy, radio frequency (RF) and kinetic energy. Using energy harvesting technologies to convert these otherwise wasted ambient energy sources into usable electricity is viable to provide a sustainable power supply for wireless sensor networks, thereby reducing their reliance on batteries, which have a limited lifespan and require periodic replacement. These energy sources can be harvested by various transduction mechanisms. Some well-known energy sources such as solar and thermal are dependent on the weather. As the concept of smart cities aims to benefit the people in the cities, another source of energy that is dynamic and available whenever there is a presence of human comes from the activities of people in the cities, which is also a source of kinetic energy. Therefore, this chapter focuses on kinetic energy harvesting because of its ubiquitous presence in urban environments and high energy density.

Kinetic energy can be converted to electricity by using piezoelectric, electromagnetic, electrostatic and triboelectric transduction mechanisms. Piezoelectric energy harvesters exploit the inverse piezoelectric effect of various materials, which develops electrical charges upon a mechanical deformation. The most commonly used piezoelectric materials for energy harvesting are piezoelectric ceramics (e.g. lead zirconate titanate, PZT for short) and piezoelectric polymers (e.g. Polyvinylidene fluoride, PVDF for short). The electromagnetic energy harvesters work on the Faraday's law—the relative motion between an electrical coil and a permanent magnet produces a varying magnetic field in the coil and therefore an electrical potential. A special type of electromagnetic energy harvester is rotary electrical motor used in the generator mode. Electrostatic energy harvesters use a capacitor to convert the displacement to electrical energy. For instance, if the voltage of the capacitor is kept constant, the decrease of the distance between the electrodes of the capacitor, caused by mechanical vibration, leads to the increase of electrical charges and thus electrical energy stored in the capacitor. Triboelectric energy harvesters rely on the triboelectric effect— certain materials become electrically charged after they are in contact with and then separated from a different material.

Kinetic energy in urban environments exists in various forms, such as the human activities, running vehicles, in-pipe water flow, airflow and structural vibrations. A brief review of energy harvesting from these sources is provided below.

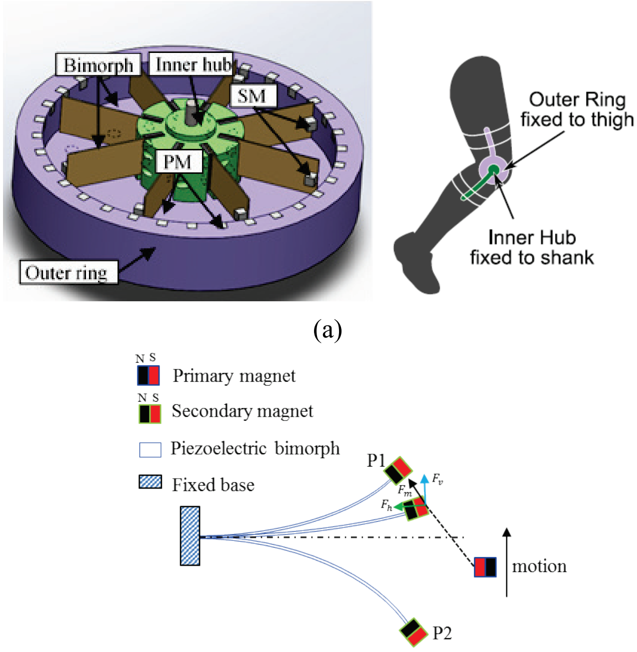
2.1 Kinetic Energy From Human Activities

Human activities are sources of thermal and kinetic energies. The human body retains a temperature which is usually different from the ambient. The temperature gradient between the body and the ambient can be converted by thermoelectric energy harvesters, producing power level in the range of several microwatts. However, drawing too much heat away from the human body will have an adverse effect to the body part [3]. Kinetic energy, which is generated by using muscles in the form of breath, blood pressure and various motions, is more abundant than the thermal energy. It has been estimated when a 68 kg man walks at 2 steps per second, as high as 67 W of mechanical power is available from the heel [3]. The motion of arms, knees, hips and centre of the upper body all possess a considerable amount of mechanical energy. Due to the abundance of the kinetic energy from human activities and the strong demand in self-sustainable energy sources for wearable electronics, kinetic wearable energy harvesting has been a hot spot in the research community. In fact, the idea of smart cities is about improving the experience and living standard of the people. Therefore, wearable devices are central to the realisation of smart cities [4]. All the transduction mechanisms for kinetic energy harvesting have been applied to wearable energy harvesters, aiming to establish self-powered wearable devices as well as wireless body sensors for the long-term monitoring of body conditions such as vital signs, daily activities and gait patterns.

Wearable energy harvesters based on electrical generators can produce average power of a few watts at normal walking speed. These energy harvesters are either mounted on the knee-joint to harvest energy from the flexion and extension of the knee-joint during a gait cycle or worn as a backpack to harvest the energy from the displacement of the upper body during walking. It has been noticed that during a gait cycle, the muscles performs positive work to accelerate the movement and negative work to decelerate the movement. A regenerative wearable energy harvester that is based on electromagnetic mechanism has developed where it is disengaged when the knee-joint performs positive work and engaged when the knee-joint performs negative work [5]. When engaged, the energy harvester, driven by the knee-joint motion, generates electricity through an electrical motor, which in return helps to decelerate the movement and reduces the burden to the muscles. With a 1.6 kg energy harvester worn on each leg, the wearers walking at a speed of 5.4 km/h produced 4.8±0.8 W of power. This electrical power was produced at the cost of additional metabolic loss of 5±21 W compared with the case of walking with the energy harvester always disengaged. Another proposed wearable energy harvester is a backpack with a 38 kg of moving mass [6]. During walking, the mass moves linearly with the centre of the upper body. This linear motion is transformed to the rotation of an electrical generator through rack and pinion and produces 5.6 W when walking at 5.6 km/h.

Although wearable energy harvesters based on rotary electric motor are able to produce a few watts of electrical power, they are cumbersome and exert a significant burden to the wearer, which prevent their applications from most of the daily life activities. Therefore, most of the research on wearable energy harvesting are focused on small scale energy harvesters using piezoelectric, inertial electromagnetic and triboelectric mechanisms. Although energy harvesters with reduced size and weight produces much less power (hundreds of microwatts to a few milliwatts) than the electrical motor-based ones, they usually have less effect on the wearer and they are well-justified by the low power-consumption of most wireless sensors.

These energy harvesters can be driven by the inertial force of a proof mass as a result of the acceleration of arms, knees, ankles during walking, or by the direct force imposed by knee motion. One challenge associated with wearable energy harvesters is that the frequency of human motions (typically 0.5 Hz to 2 Hz) is much lower than the resonance frequency (tens or hundreds of Hertz) of the energy harvesters. Operating the energy harvesters away from the resonance leads to low efficiency and power generation. This is usually addressed by a strategy called frequency up-conversion. The most common example of frequency up-conversion is probably playing guitar— the player plucks the string and then the string vibrates at its resonance frequency. To implement this mechanism in energy harvesting, a polymer plectrum is used to pluck a piezoelectric cantilever [7], which is deflected and then rapidly released to free vibration at the resonance frequency. In this way, the resonance of the cantilever at high frequency can be actuated by input motion at low frequency. The plucking of piezoelectric cantilever, either by a polymer plectrum [8] or by a magnetic force [9], has been later successfully used for energy harvesting from knee-joint as shown in Fig. 1 (a) [10]. The rotation of the knee-joint motion produces a relative rotary motion between the primary magnets and the piezoelectric cantilevers. Secondary magnets were glued to the tip of the piezoelectric bimorph cantilevers. As the primary magnets passes by the secondary magnets, the repulsing force deflects the piezoelectric cantilever, which is subsequently released to resonance oscillation, as illustrated in Fig. 1 (b). With 8 piezoelectric cantilevers, the energy harvester produced 4.5 mW of power when walking at 7 km/h and a wireless sensor node with three sensors were successfully powered by the energy harvester to sample and transmit nearly 1 kilobit of data [10]. In addition to this direct force actuating, frequency up-conversion has also been used for inertial force actuating. For instance, a wearable energy harvester with a size comparable to a British one-pound coin has been developed to harvest the energy from the acceleration of human body during walking and running [11]. The inertial force due to the acceleration drives a rotary proof mass to rotate, which plucks a piezoelectric cantilever by using magnetic force in a similar way to Fig. 1 (b) and produces electric power in the range of tens of microwatts.



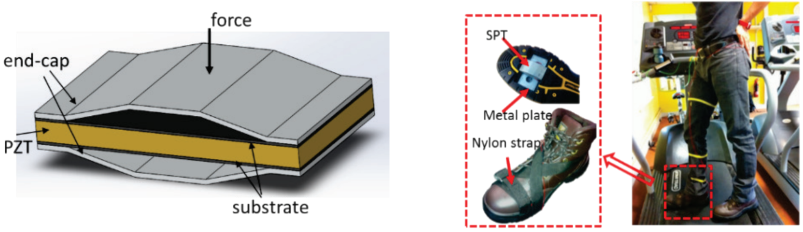
(a)

(b)

Fig. 1 (a) a schematic of the knee-joint energy harvester with frequency up-conversion by magnetic plucking [9] (b) an illustration of the magnetic plucking process [10]. *Figures reproduced under Creative Commons license.*

During walking, the force put on the ground by the foot can be a few times larger than the body weight. This large force attracts a great deal of research interest for footwear energy harvesting, the majority of which are based on piezoelectric mechanism. Piezoelectric polymer seems to be a good choice for the piezoelectric material as it has a similar stiffness to the shoe soles. However, due to the weak piezoelectric effect, piezoelectric polymer-based footwear energy harvesters, usually in the form of inner shoe soles, produce average power rarely larger than 1 mW. Piezoelectric ceramics have a much stronger piezoelectric effect and therefore have the potential to produce higher power than polymers. The piezoelectric ceramics can be used in footwear energy harvesting with a force amplification mechanism shown in Fig. 2 (a) [12]. When a vertical force is applied to apex of the end-caps, the end-caps amplifies the force and redirect it to horizontal. The amplified force is applied to the piezoelectric ceramics (PZT in this case). As the electrical power output of a piezoelectric energy harvester is proportional to the square of the input force, the amplification of the input force increases the electrical power output. When mounted in a shoe sole as shown in Fig. 2 (b), the energy harvester produced average power of 2.5 mW when walking at 4.8 km/h. In another study, when four footwear energy harvesters with force amplification mechanism were installed in the heel, 20 mW of power was recorded at a walking speed of 4.8 km/h [13].

In addition to powering wearable electronics, energy harvesting from human activities can also be used for various other purposes. The press-button motion can be converted to electric energy by using either piezoelectric [14] or electromagnetic [15] methods to power wireless switches and door bells. The electrical energy produced by each press-button motion is between 100 to 200 μJ, which is enough to send a RF signal. The footsteps on floor tiles can be harnessed to create self-powered occupancy sensors for smart buildings [16] or even to power street lights, displays, speakers, alarms, signs or advertising when rotary electrical motor is used to produce high power levels [17].



(a) (b)

Fig. 2 Sandwiched piezoelectric transducer (SPT) for footwear energy harvesting (a) a schematic of the SPT (b) the SPT mounted in a shoe sole for experimental testing [12]. *Figures reproduced under Creative Commons license.*

2.2 Running Vehicles

Running vehicles dissipates a significant amount of kinetic energy in the form of vehicle vibration, road surface and tyre deformation, and high-speed air flow, all of which are good candidates for energy harvesting. Particularly, there is growing interest in harvesting energy from running vehicles to provide sustainable power for wireless tyre pressure monitoring systems (TPMS) as TPMS are becoming increasingly mandatory in automotive market to ensure the safe and efficient use of tires [18]. The primary energy source for TPMS is the rotating wheels since they are located at where the power is needed. The energy harvesters can be driven by acceleration through the inertial force acting on a proof mass or dynamic strain through the tyre deformation. Piezoelectric patch can be mounted on the inner liner of a tyre to convert the circumferential deformation of the tyre to electricity [19]. When a load of 500 kg was applied to the tyre by a car driving at 60 km/h, 380 μJ of energy was produced in each revolution.

Embedding energy harvesters under road surfaces and speed bumps has also attracts certain interests recently. One of the proposed research was to integrate a piezoelectric cymbal energy harvester with diameter of 29 mm in asphalt [20]. Experimental showed 16 μW can be produced by the passing of a single vehicle. It was estimated that integrating 30,000 energy harvesters in a 100 m road could produce 40-50 MWh/m^2 within a relatively low cost. A speed bump energy harvester that converts the linear upward and downward deformation of the speed bump to the rotation of an electrical motor was also developed [21]. In-field test showed that the energy harvester could produce up to 1120 W peak power by a low speed vehicle and had the potential to power road-side electrical device for smart transportation network.

2.3 In-pipe Water Flow

Pressurised water supply in modern cities provides a good opportunity for energy harvesting. Harnessing clean energy from the excess head pressure from the in-pipe water flow enables the deployment of battery-less wireless sensor networks to monitor water quality, leakage and pipe integrity so as to improve water supply management and safety. Energy harvesting from in-pipe water flow generally has been implemented by either piezoelectric or hydro-generators.

Piezoelectric cantilevers can be submerged in the water flow to harvest energy. The unsteady fluid flow such as vortex and turbulence caused by the cantilever or the pipeline itself drives the piezoelectric transducer to oscillate [22, 23]. The reported power output of piezoelectric energy harvesting in fluid flow are from a few microwatt to a maximum of 25 mW [24], where a force amplification mechanism was used. When harvesting fluid flow energy by piezoelectricity, at least part of the energy harvester has direct contact with the travelling fluid. This intervenes the fluid flow and causes pressure drop. For example, when producing 25 mW of power from air flow, a pressure drop of 300 kPa was recorded [24]. Another strategy is to harvest the pressure ripples caused by pumps and actuators. Through aluminium diaphragm interface, the dynamic ripples were turned to a dynamic force applied to a piezoelectric stack and up to 1.2 mW was recorded [25, 26].

Hydro-generator is a well-established technology in large scale. However, research is still going on to develop high-efficient generators working at low flow-speed and with the power output in the range of milliwatts to a few watts. A few studies have been attempted by optimising the turbine or turbine housing to reduce the start-up pressure of the generator. With an optimised turbine housing for a commercial hydro-generator, 10 mW of power was produced at the flow rate of 5.5 L/min and 200 mW at 15 L/min [27]. A vertical axis water turbine to generate power from water pipelines for water quality monitoring was also proposed [28]. With an optimised turbine, the generator was able to produce up to 88 W in a water pipe with diameter of 100 mm and water speed of 1.5 m/s.

2.4 Airflow

Airflow or wind energy is one of the most abundant renewable energy sources. While huge wind farms have been used to provide a substantial contribution (e.g. 15% in the UK) to the power grid, small scale air flow energy harvesters with power output in the range of milliwatts have also been researched. In urban environments, the airflow can either occur naturally or induced by human activities. Therefore, the generated energy can be used to provide localised power sources for sensors to monitor the conditions of infrastructures, collect weather data etc. These wind energy harvesters can be flexible piezoelectric material or composites and electromagnetic mechanism to produce electricity. One popular configuration of flexible piezoelectric energy harvesters is piezoelectric flags. A piezoelectric flag may consist of cantilever beams bonded with a piezoelectric patch such as macro fibre composites (MFC) or fabricated completely with a flexible piezoelectric polymer [29]. The aerodynamic instabilities of the flags deform the piezoelectric material to produce electricity. This leads to a solid-state energy harvester design with a simple structure and lightweight.

Electromagnetic based energy harvesters can be similar to the piezoelectric ones where the energy harvesters consist of a cantilever, a coil and a magnet [30]. Again, by relying on the aerodynamic instabilities of the flapping energy harvesters, the cantilever with the magnet at its tip moves up and down through the coil to produce electrical energy [31]. Similarly, the output power range is around hundreds of microwatts to tens of milliwatts. To obtain a higher output power, electromagnetic based energy harvesters that use an electrical generator connected to a turbine have been reported where more than 100 mW of electrical power can be generated [32]. The energy harvesters can harvest airflow induced by fast moving objects such as trains in the underground [33] or directly from ventilation systems [30] to power up wireless sensors that monitor important parameters in those locations.

2.5 Structural Vibrations

All the aforementioned energy sources may have a direct impact or indirectly propagate towards some surrounding structures or buildings. For example, human activities within a building [34] or vehicles moving on a bridge [35] will exert some energy towards the supporting structures, which cause them to vibrate. Given that building structures might experience large exerted forces but do not vibrate vigorously at high frequency, a way to harvest energy from structural vibration is by harvesting the strain experienced by the structures. The range of peak-to-peak strain levels can be around 300 $\mu\varepsilon$ to 600 $\mu\varepsilon$ at frequencies of less than 1 Hz to up to 10 Hz. MFC is an ideal candidate for strain energy harvesting for its flexibility that enables adhesion onto structures with different curvatures. It can be used as a strain sensor for structural health monitoring [36]. A complete strain energy harvesting powered wireless sensor node that uses the MFC as the energy harvester sensors managed to harvest 0.5 mW to 3.38 mW of power from the aforementioned vibration range [37]. To further increase the output power from the energy harvester, an auxetic layer can be included as the interface between the MFC and the host structure [38]. With the auxetic structure, a power gain of up to 14.4 times was observed.

3 Power Management for Energy Harvesting Systems

There is always a minimum energy requirement and a certain voltage and current operating range for any devices to work properly, with no exception to wireless sensors. Given that many of the energy sources that are available to be harvested are usually sporadic and temporal, the use of power management circuits are necessary in between the energy harvesters and the wireless sensors. The power management circuits condition the energy from the energy harvesters to a form that is usable by the wireless sensors. To do so, power management circuits have several essential functional blocks as shown in Fig 3.

The four main parts of a power management circuit are a voltage converter, a maximum power point tracking (MPPT) circuit and a charge management circuit. The voltage converter can be a rectifying circuit that converts any of the electrical energy from the energy harvesters that is alternating current (AC) into direct current (DC). Then, a DC–DC converter will be used to convert the rectified DC voltage from the rectifying circuit into another DC voltage level that is suitable for the energy storage device and wireless sensors. In the case that the output from the energy harvesters is already DC, the rectifying circuit is not required. The MPPT circuit controls the operation of the DC–DC converter to transfer maximum power from the energy harvesters to the rest of the system. Finally, the charge management circuit ensures that sufficient energy for the wireless sensors to complete a predefined task is accumulated in the energy storage device before the energy is released to the wireless sensors. It should be noted that the energy storage device is include as part of the charge management circuit here because the energy flow from the energy storage device to the wireless sensors is managed by the charge management circuit. Also, the energy storage device itself is usually a single element such as capacitors or batteries that does not have any other functionality apart from storing the harvested energy. In latter subsections, the operating principles of these functional blocks will be discussed. Some examples of the state-of-the-art techniques will also be given.

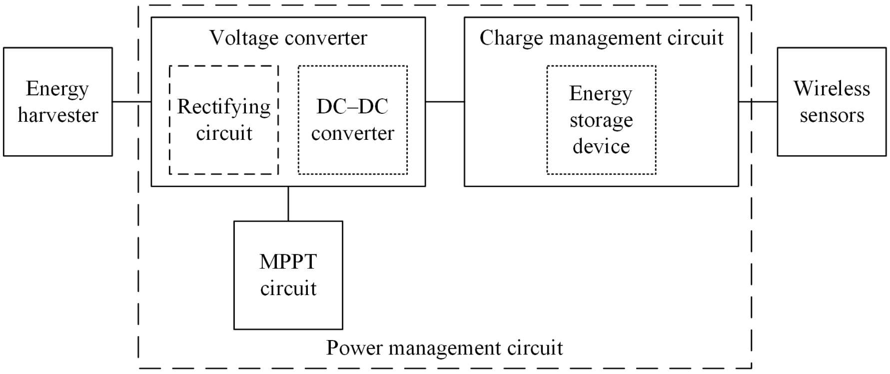


Fig. 3 Block diagram of a power management circuit showing its main functional blocks and their links to the energy harvester and wireless sensors.

3.1 Voltage Converter

Generally, the conversion of AC-to-DC and DC-to-DC is a very common topic in power electronics. However, as it can be seen from Fig. 3, the voltage converter serves as the first interface that interacts with the energy harvester. Therefore, it is a part that cannot be taken lightly. The conversion from one DC level to another DC level can be either from a lower DC level to a higher DC level, which is known as step-up or from a higher DC level to a lower DC level, which is known as step-down. Boost converters are used to step-up the DC voltage whereas buck converters are used to step-down the DC voltage. A DC-to-DC converter that is capable of stepping up and stepping down a DC voltage is known as a buck-boost converter. Similar circuits, techniques or methodologies for DC-to-DC conversion in other electronic applications still apply in energy harvesting, and therefore will not be further discussed here.

On the other hand, the AC-to-DC conversion, which is also known as rectification requires more attention. A rectifier converts the waveform from both positive and negative half cycles of an AC waveform into a pulsating DC signal. A smoothing capacitor is usually put at the output of the rectifier to smooth out the pulsating signal so that the rectified DC voltage has less fluctuation since it is preferred to have a steady power supply for the operations of the electronics. Rectifiers are usually capable of taking in DC input and still provide a DC output that is similar to the input but with some losses where the output is slightly lower than the input. Therefore, it is viable to include a rectifier in any power management circuits for energy harvesting systems. The simplest rectifier is consists of only diodes. This type of diode-based rectifiers are also known as passive rectifiers because they do not require any power supply for their operation. However, due to the intrinsic characteristic of diodes, the output voltage of passive rectifiers is always lower than their peak input voltage by a minimum of around 0.3 to 0.7 V [37, 39]. This voltage loss can be very significant to some energy harvesters as their output voltages would be around that amplitude as well [40, 41]. This means when passive diode-based rectifiers are used to convert the AC outputs from these types of energy harvesters to DC, there will be significant losses on the energy transfer from the energy harvesters or no output from the rectifiers at all.

To overcome the limitation of passive diode-based rectifiers, switches based on metal-oxide semiconductor field-effect transistors (MOSFETs) are used in place of the diodes. The switches are turned on or off appropriately to direct the flow of the AC output from the energy harvester into a unipolar voltage. Since the switching requires energy and some sort of control, this type of rectifying circuit is known as active rectifier. The voltage drop across the switches is proportional to the resistance of the switches and the square of the current flowing through them, which is usually quite small. Therefore, active rectifiers are capable of rectifying very low voltages from energy harvesters that are near to zero volts. However, there is a minimum voltage and power requirement for active rectifiers to start operating. In the case of energy harvesting, especially when the systems are batteryless where all the energy comes from the energy harvesters, there is still a requirement for the active rectifier to be able to deal with the raw output from the energy harvesters to start operating. In many cases, the minimum start up voltage for the active rectifiers is actually similar to the voltage drop of a diode [42-44]. Also, many of the active rectifiers for energy harvesting applications have limited voltage operating range that can be lower than the maximum output voltage range of certain energy harvesters [42, 45].

Commonly used rectifiers are full-wave bridge rectifiers and voltage doublers. Full-wave bridge rectifiers usually consists of four MOSFETs or diodes where two of them are used for rectifying one half-cycle of the AC waveform. Therefore, the output of full-wave bridge rectifiers is lower than the peak amplitude of the input. A voltage doubler as its name suggests can amplify the input voltage from energy harvesters and provide a rectified output voltage that is almost double of the input voltage. Voltage doublers can also start operating with a lower voltage from the energy harvesters as the electrical energy goes through less diodes or switches than full-wave bridge rectifier. To deal with the possible wide voltage range from energy harvesters, configurable rectifiers that combine the two aforementioned different rectifying circuit topologies were proposed [46, 47]. Therefore, configurable rectifiers can deal with a wider voltage range than conventional single topology passive or active rectifiers by reconfiguring themselves into the appropriate topologies based on the voltage from the energy harvesters. Configurable rectifiers use the voltage doubler topology when the voltage is below a predetermined threshold and use the full-wave bridge rectifier topology when the voltage exceeds the threshold. These two rectifier topologies can be switched to one another without much complexity. For example, by adding a switch to a passive full-wave bridge rectifier, the rectifier can be configured as a voltage doubler whenever the switch is turned on [47]. Similar to other single topology rectifiers, configurable rectifiers can be implemented based on MOSFETs [46] or diodes [47]. Therefore, configurable rectifiers can be built using different circuit implementations as required by the applications. This is particularly well-suited for energy harvesting systems as their design are often application specific.

3.2 MPPT Circuit

Due to the usually low and non-continuous output from energy harvesting, it is necessary to collect as much energy as possible from the energy harvesters. Therefore, an MPPT circuit is indispensable in the power management circuit for energy harvesting systems. Maximum power transfer from the energy harvester occurs when the input impedance of the circuit that is connected to the energy harvester matches the impedance of the energy harvester. The effective impedance of a DC–DC converter changes with its duty cycle [48]. Therefore, the general operating principle of an MPPT circuit is to control the switching of a DC–DC converter at an appropriate rate that achieves maximum power transfer. In terms of actual implementation, many different techniques have been proposed. Some popular methods in energy harvesting applications include hill-climbing [49, 50], perturb and observe (P&O) [51, 52] and fractional open-circuit voltage (FOCV) [53, 54]. All these techniques can be generally grouped into two categories. The first type is sort of a trial-and-error based where the MPPT circuits iteratively sample the voltage and current from the energy harvesters to calculate the harvested power, compare the newly calculated power with the previous one and change the operation of the DC–DC converters until the highest power is obtained. The hill-climbing and P&O are under this first category. The second one, which applies on FOCV, is an *a priori* method based on the findings from previous researches that maximum power transfer occurs at certain ratio of the open-circuit voltage of energy harvesters. For example, maximum power transfer usually occurs at around 0.75 to 0.8 open-circuit voltage of solar panels [50] and at the half open-circuit voltage of thermoelectric generators [55], piezoelectric energy harvesters [36], electromagnetic energy harvesters [56] and radio frequency rectennas [57]. This method first samples the open-circuit voltage of the energy harvesters by disconnecting the energy harvesters from the DC–DC converter and then obtains the FOCV from the sampled open-circuit voltage to be used as the reference voltage.

As it can be seen, both categories of MPPT require more than one cycle to determine the MPP of the energy harvesters since they need to do some sampling first. Also, the capability of the system to actually harvest energy at the MPP of the energy harvesters is dependent on the frequency of the sampling phase. This is because the system will only harvest energy at the condition as determined by the MPPT circuits based on the earlier samples until the next sampling phase. Any changes to the power from the energy harvesters in between two successive sampling phases will not change the MPP as perceived by the MPPT circuits immediately. Therefore, an MPPT circuit that has a long gap time between successive sampling phases is less likely to respond effectively and make the DC–DC converter to harvest energy at the MPP of an energy harvester which its output changes dynamically [50]. The MPPT circuit may take samples more frequently so that most of the changes from the output of the energy harvester can be tracked. However, this comes at a cost of a higher power consumption of the circuit. Also, for some energy sources that occur sporadically for a very short time such as from a fast moving vehicle where the energy harvester is fixed under the road, the energy could have already disappeared after the MPPT circuits take numerous cycles of sampling phases to find the MPP.

Given that the FOCV method usually takes less cycles than the other category of MPPT, an innovative method that based on FOCV was developed. Conventional FOCV method requires two steps, which are to sample the open-circuit voltage and obtain the appropriate voltage ratio that corresponds to the MPP of energy harvesters. The method directly determines the ratio of the voltage that corresponds to the MPP of energy harvesters from the voltage profile at the smoothing capacitor [53]. Any changes at the output of energy harvesters will directly be reflected on the voltage profile of the smoothing capacitor. Therefore, this method can respond to the dynamic changes from the output of energy harvesters. The power consumption is less than 10 μW and the MPPT efficiency is up to 98.28%. As the open-circuit voltage of some energy harvesters can be quite high [58], the requirement of sampling the open-circuit voltage of the energy harvester using the conventional FOCV method would mean that high voltage rating components or fabrication technologies are required, which can be expensive or even not possible to be fabricated [59, 60]. Therefore, another advantage of directly determining the FOCV of the energy harvester is that the circuit can be implemented with lower voltage rating components, which are usually smaller and cheaper. This should also be an important consideration as well given that the total costs a proliferation of energy harvesting powered wireless sensor nodes and their installation should be lower than their wired counterpart for the energy harvesting powered wireless sensor nodes to become attractive and viable for widespread deployment.

3.3 Charge Management Circuit

In energy harvesting applications, capacitors are often used as the energy storage device for their higher charge-discharge cycles and higher tolerances against unregulated input voltage or current over rechargeable batteries. However, unlike batteries, which are also a type of energy source, capacitors need to be charged up first and can only provide as much energy that has been stored in the capacitors. Given that the instantaneous power from energy harvesters is usually insufficient for the operation of wireless sensors, it is necessary to accumulated the harvested energy in the energy storage capacitor first. Once sufficient energy has been accumulated, the charge management circuit releases the energy from the capacitor to the wireless sensor. Without the charge management circuit, it is unlikely that energy can be accumulated efficiently as the wireless sensors will constantly drain the energy from the energy storage capacitor [61]. This will cause the wireless sensors to unable to start-up at all. Therefore, circuits that mainly consist of switches were initially proposed to allow energy accumulation for the start-up of wireless sensors [62, 63]. The start-up circuits simply connect the energy storage capacitors to the end devices when their voltages reach a preset threshold. The end devices will be disconnected from the capacitors when the voltages drop below the threshold. However, a single threshold is inadequate as the capacitor voltage may drop below the threshold as soon as energy is drained from the capacitor. The start-up circuits may keep toggling around their threshold voltage without actually powering up the end devices, which waste energy.

A more practical circuit consists of two different thresholds [61, 64]. The turn-on threshold voltage is higher than the turn-off threshold voltage by at least a few hundreds of millivolts. By having the two different thresholds, there will be time for the end devices to perform their tasks before the voltage drops to the turn-off threshold. Still, relying solely on the threshold voltages is not enough to manage the charge usage efficiently, with two potential issues. First, the end devices can be disconnected from the energy storage capacitor before finishing their tasks. Secondly, the end devices stay on doing nothing but keep draining the energy until the capacitor voltage drops below the turn-off threshold after finishing their tasks early. By complementing the hardware with energy-aware software programme that allows the end devices to determine the usable energy capacity in the energy storage capacitor [61], the harvested energy can be better used. This allows the end devices to adjust their tasks accordingly based on the energy capacity before the capacitor voltage reaches the turn-off threshold. The execution of energy-aware algorithms require a microcontroller, which is usually the end devices. So, some extra pins are required in the charge management circuit for the control by the microcontroller. Although it seems like the end devices need to spend some energy for the execution of the algorithms, the energy saved by avoiding the aforementioned two cases is far more than the energy spent.

Apart from the energy-aware approaches that make efficient use of the harvested energy before the capacitor voltage reaches the turn-off threshold, the turn-on threshold also requires attention. An improper choice on turn-on threshold voltage reduces the energy transfer from the DC–DC converter to the energy storage capacitor [65]. If the selected turn-on threshold voltage is very close to the maximum output voltage of the DC–DC converter, the energy transfer efficiency will reduce. It is the nature of DC–DC converters to provide a steady DC output voltage. Therefore, as the capacitor voltage is close to the maximum output voltage of the DC–DC converter, the DC–DC converter will transfer less energy to its output so that the voltage can slowly build-up at its output so that it does not exceed the predetermined output voltage. This process is undesirable for energy harvesting which usually has low power as it would make even less energy to be accumulated in the capacitor. Therefore, by setting the turn-on threshold lower than the voltage region where the DC–DC converter starts to regulate its output voltage, the harvested energy from the energy harvester can be transferred to the energy storage capacitor at higher efficiencies [65].

4 Wireless Sensing and Communication

Information and communication technologies (ICTs) are the foundation of smart city development [66] as ICTs enable smart cities to collect data from smart devices and sensors embedded in roads, power grids, buildings and so on. There are many established wireless technologies such as ZigBee, Bluetooth Low Energy (BLE) and Wi-Fi for connected devices but they are only suitable for short distance wireless communication. To cover the entire city, these services may have thousands of remote sensors spreading all over the city that has an area of kilometre square. As a result, long range wireless protocol is needed to have that wide connectivity coverage. Therefore, Low-Power Wide-Area Network (LPWAN) is gaining increasingly popularity for smart city applications since LPWAN technology has successfully exhibited wide area connections from several kilometres to tens of kilometres. Also it is expected that their market will be huge where it is estimated that a quarter of nearly 30 billion Internet of Things (IoT) / Machine to machine (M2M) devices will be connected using LPWAN [67]. Moreover, LPWAN technology can be used in combination with energy harvesting technology because of its low data rate, low power consumption, and low throughput characteristics, which meets the demands of smart cities for expansion of the IoT exploitation and to overcome the current limitations in power supply and application deployment scope. There are a few prominent technologies in the LPWAN space such as Sigfox), NB (Narrow band)-IoT and LoRa (Long Range) [68]. SigFox is a proprietary LPWAN technology that supports very low data rate compared to other LPWA technologies where only 140 12-bytes message can be transmitted per day. NB-IoT does not have the limitation on the number of messages that can be transmitted and have a much higher date rate than Sigfox. However, NB-IoT is operating using licensed protocol, which can be costly in long term. LoRa is the latest technology that does not have limitation on the number of transmissions and is operating in the license-exempt spectrum. Therefore, LoRa is identified as the most promising technology for smart city applications and will be reviewed and discussed in this subsection.

4.1 LoRa for Smart City Applications

LoRa is a low-power wide-area network protocol for IoT applications based on chirp spread spectrum technology (CSS) with a broader band, which is defined by the LoRa Alliance [69]. LoRa transceivers use license-free sub-GHz frequencies for their communication, which include 169MHz, 433 MHz, 868 MHz (Europe), and 915 MHz (North America) industrial, scientific, and medical (ISM) radio bands [70]. The LoRa modulation between the physical and Media Access Control (MAC) layer is a Semtech proprietary technology that includes two basic techniques: forward error correction techniques of code rate to further increase the receiver sensitivity and multiple orthogonal spreading factors (SF) to provide a trade-off between data rate and range [71]. Moreover, LoRa utilises a wider band, usually of 125 kHz or more, to broadcast the signal, which allows the usage of scalable bandwidth (BW) of 125 kHz, 250 kHz, or 500 kHz to make LoRa more resistant to channel noise, long term relative frequency, doppler effects and fading [72]. Also, LoRa protocol is designed specifically for low power consumption, typical 15 mW for receiving and 108mW for transmission [71].

The basic network architecture of a LoRaWAN consists of LoRa end devices, LoRa gateways, and a LoRa network server [73]. The network makes use of star topology in which LoRa gateways are transparent bridges. The LoRa end nodes communicate with gateways that employ LoRa with LoRaWAN. LoRa gateways pass raw LoRaWAN packets from the end nodes to a LoRa network server with a high throughput based on the backhaul interface, which is typically the third generation (3G) of a wireless mobile telecommunications network or Ethernet. LoRa gateways also act as a bidirectional communication or protocol adapter with the LoRa network server. In this case, the LoRa network server takes charge of decoding the data packets transmitted by the LoRa devices and creates the frames that would be directed back to the devices. The following sections will further explain the features of LoRa that make it suitable for smart city applications from five aspects: long-range connectivity, low-power, low-cost, good reliability and robustness and large potential scale [68]. After that, several typical examples of LoRa for smart city applications in the area of academic research and commercial market will be presented.

4.1.1 Long Range Connectivity

In contrast to traditional short-range wireless sensor networks, LoRa technology is designed for a wide area coverage and an excellent signal propagation to hard-to-reach indoor places such as basements [74]. Quantitatively, demodulation is possible with a noise level of less than 20 dB, which allows the end nodes to connect to the gateways at a distance ranging from a few to tens of kilometres depending on their deployment environment of in rural or urban. Compared to the 2.4 GHz band of traditional short-range technologies, LoRa uses sub-1 GHz band in which the lower frequency signals have better propagation characteristic through obstacles such as concrete walls and less congested. For examples, three commercially available LoRa wireless communication transceiver modules of RN2483 from Microchip, SX1273 from SEMTECH, and eRIC-LoRa from LPRS proved the capability of LoRa's long-range connectivity. The transmission range of RN2483 is up to 15 km coverage in suburban and up to 5 km coverage in urban area [75]. The line of sight ransmission range of SX1273 is up to 48 km and more than 3 km in dense urban environments [76]. The line of sight transmission range of eRIC-LoRa is up to 10 km [77].

4.1.2 Low Power

Mesh topology has widely employed for expanding the coverage of short range networks such as in BLE and ZigBee. It is a complex and expensive network, where all end nodes cooperate to distribute data amongst each other. It consists of a cluster of self-forming multi-hop mesh nodes and an access point node that connects the nodes to the gateway. Nodes are capable of two way communication and collect and relay data. The data is propagated along a path by hopping from node to another node until it reaches its destination. However, there are three major disadvantages. First, their deployment cost is high to connect huge number of devices which are geographically dispersed in a wide area range [78]. Second, for a subset of nodes in the mesh network, they have to undertake not only the tasks of sampling and communication with the gateway, but also need to communicate with other nodes to transmit the data through multi hops towards a gateway, which increase their energy consumption excessively [79]. Finally, the mesh network needs to have several nodes staying in the active state at the same time, which is difficult in the energy harvesting powered wireless sensor network since the active time of the nodes is very short due to energy limitation. In most cases, only a few nodes are active and remain in the network for a short time [80].

The limitations of short range networks especially in their energy requirement are surmounted in LoRa technology. LoRa uses several methods to achieve low-power operation. The major method is that LoRa nodes usually form a star topology, eliminating the energy consumed by packet routing in multi-hop networks. Also, node design is simplified by shifting complexity to the gateway. With its star network and long-range communication capability, the end nodes deployed in its coverage region are directly connected to the gateways with reliable links. Unlike mesh topology, the star network topology enables most of the network functions, such as the communication time and the frequency slot of each nodes to be given to the gateways, which is helpful to reduce the energy consumption of the nodes in the network [79]. It also allows an immediate and direct access from the node to the gateways since gateways are always-on. Finally, the impact of a transmission failure due to a single failed node, and thus energy wastage can be reduced by independently connecting each node to the gateways. The failure of a transmission linking any node to the gateways will result in the isolation of that single node from all others, but the rest of the nodes in that network will be unaffected. If mesh topology is adopted as in the case of short range network, the energy of all the nodes that have their transmissions hopping through a node that fails will be wasted as all of the data will be lost.

4.1.3 Low Cost

LPWAN hardware cost per terminal is kept below $5 and the connectivity subscription fee per unit is as low as $1 [74]. LoRa technology mainly adopts three methods to reduce capital expenditures and operating expenses of end users and network operators by reducing the hardware complexity, mass production of the devices and using minimum infrastructure [68]. Firstly, compared with cellular and short-range wireless technologies, LoRa transceivers only need to handle less complex waveform, which enables them to reduce transceiver footprint, peak data rates, and memory size, thereby minimising hardware complexity and cost. Secondly, given that it is widely known that many devices will be required for smart city applications, LoRa chip manufacturers are mass producing the devices so that the cost can be reduced through economies of scale. Finally, LoRa gateways can connect to thousands of devices over the range of several kilometres can operate on unlicensed spectrum. This means the requirement to install new gateway, which is linked to servers and the Internet is low and there will be virtually no or very low operating cost once the wireless sensor nodes are deployed.

4.1.4 Good Reliability and Robustness

LoRa are designed to provide reliable communications. LoRa use robust modulation and spread spectrum technology to improve the anti-interference ability of the signal and provide some security. In the spread spectrum, narrowband signals spread in the frequency domain with the same power density, resulting in wider bandwidth signals. Moreover, it provides an embedded end-to-end AES128 encryption and high capacity, which is able to support millions of messages per gateway [81].

4.1.5 High Scalability Potential

LoRa / LoRaWAN has great expansion potential because it avoids multi-hop topologies and uses narrow bands to support a large number of devices to effectively use limited spectrum [74]. In a typical case, LoRaWAN can handle 120 nodes in a 3.8 hectare area [82], but if the LoRaWAN is able to use dynamic transmission parameter selection such as the adjustment of SF and BW or multiple receivers, its scalability can be even higher [68]. As the node design has been simplified, it is envisaged that the dynamic transmission parameter selection function will be carried out by the network manager or the gateway.

4.2 Example Applications

While the deployment of LoRa based networks is still in its infancy, there are several successful examples both in the academia and the commercial market that show the viability of energy harvesting powered LoRa networks for smart city applications. These examples include building monitoring using thermal energy harvesting, urban greenhouse gas monitoring using solar energy harvesting, bridge monitoring using vibration energy harvesting and many more, which will be briefly reviewed below.

4.2.1 Building Monitoring

A self-powered LoRa wireless sensor node driven by a flexible thermoelectric generator, which can be wrapped around heat pipes with various diameters has been demonstrated [83]. The fabricated thermoelectric generator has an area of $140 \times 113 mm^2$ and is able to harvest 272 mW of power from a heat pipe at a temperature of 70 °C. The sensor node consists of one MSP430FR5994 microcontroller from Texas Instruments, one LoRa wireless transceiver (SX1276) from Semtech and three sensors: a carbon dioxide (CO_2) and volatile organic compounds (VOCs) sensor (CCS811) from AMS, an ambient temperature and humidity sensor (HTU21D) from Measurement Specialties and heat pipe temperature sensor (NTFS-1) from Bo Yuan Electronic. The harvested energy is able to power the sensor node to monitor the heat pipe temperature, ambient temperature, humidity, CO_2 and volatile organic compound concentrations and wirelessly transmit the data at distances as far as 500 m.

4.2.2 Urban Greenhouse Gas Monitoring

A solar panel powered LoRaWAN to measure urban greenhouse gas emissions in Nordic cities was developed [84]. It is a low cost automated system for greenhouse gas emissions monitoring network around their city. The data from the nodes are transmitted to the cloud, through the LoRaWAN. An initial deployment consists of around 10 nodes for a city of the size of Trondheim. Sensor nodes were equipped with different sensors to measure different parameters of gasses: CO_2, Nitrogen Oxides (NO_x), temperature, pressure, humidity, and combined particle matter (PM) PM1, PM2.5 and PM10. The gateway antennas were deployed in central and elevated locations such as on the roof of the Student Society building in Trondheim to have a better network coverage of the city. The payload of the data is compressed to 54 bytes, which is the lowest data rates and was sent 12 times a day.

4.2.3 Bridge Condition Monitoring

An electromagnetic vibration energy harvester powered LoRa wireless sensor to monitor road condition and measure the temperature of the asphalt and the presence of water or rain has been developed [85]. The sensor node consists of one STM32L053R8 microcontroller with ARM Cortex M0+ from ST Microelectronics, rain and temperature sensor and one RN2483 LoRa module from Microchip with 434 and 868 MHz antennas. 330 mJ of energy can be harvested from vibrations on the bridge in a duration of about 3.5 hours (7 vehicles every 50 seconds). The total energy required for a complete transmission is about 124 mJ, which is less than half of the harvested energy. The system shows good performances for energy harvesting powered LoRa sensors in real conditions.

4.2.4 Urban Water Meter Monitoring

Fenix Hub 200 from Aqua Robur is used to the monitor the water distribution network and can be placed anywhere along pipe network [86]. Typically, it consists of an energy harvesting turbine which is installed into the water pipeline to extract energy from the flow in the pipe (up to 10 W output from generator and generating energy in flows as low as 0.1 m/s), one LoRaWAN wireless transmission module (transmitting up to every 120 seconds) and several sensors on the water market. Fenix Hub 200 is able to collect data from a pressure sensor, temperature sensor, water quality sensor, dedicated magnetic flow meters and then use the built in radio to communicate with the cloud platform.

4.2.5 Urban Environmental Monitoring

A solar panel powered wireless sensor network based on LoRa protocol has been demonstrated [81]. The network consist of one gateway and two sensor nodes. Both nodes include an 8-bit microcontroller ATMega328 from Atmel, a real time clock DS1302 from Maxim Integrated, a wireless communication module RN2483 from Microchip. In terms of the sensors, one node has a temperature and humidity sensor HDC1080 from Texas Instruments, an ambient light sensor TEMT6000 from Vishay, a carbon monoxide sensor MQ7 from Winsen and a smoke sensor

MQ2 from Winsen. Another sensor node has a methane CH_4 sensor MQ4 from Winsen, an alcohol sensor MQ3 from Winsen and the same HDC1080 and TEMT6000 sensors as in the other sensor node. Both sensor nodes are powered by a 3.7 V battery with 2600 mAh capacity combined with a 3.5 W solar panel with a maximum of 6 V output. The gateway is powered by using a similar combination of the 3.5 W, 6 V solar panel and a 3.7 V battery with a capacity of 4000 mAh. The distance between each node and the gateway is 800m and 500m, respectively. The gateway provides the interconnection between the nodes and cloud networking, where data is accessible by users. Experimental results show that the energy harvesting powered LoRa wireless system is completely reliable with no packet losses between system connections, and the energy provided is sufficient.

In the commercial market, there is a weather station that uses LoRaWan for its communication called "Cerere Pluvia" from Axatel [87]. It is equipped with different types of sensors to measure moisture, temperature, wind speed and solar radiation, single or double-faced leaf wetness and rain fall level. The product is powered by batteries with a total capacity of 3000 mAh that are recharged by a solar panel.

4.2.6 Human Surroundings Monitoring

A wearable LoRa wireless sensor network powered by a round solar panel that has a radius of 3 cm has been demonstrated [88]. The wearable device was developed with the aimto monitor harmful environmental conditions for safety applications. The proposed sensor node, called the WE-Safe node, consists of a microcontroller ATmega328P from Atmel Corporation, a RFM95 LoRa wireless module from Hope Microelectronics with 3 dBi antenna and multiple environmental sensors such as a temperature and relative humidity sensor BME680 from Bosch-Sensortec, a CO_2 sensor from CO_2 Meter, and an ultraviolet sensor SI1145 from Silicon Labs. WE-Safe nodes can monitor environmental data in real time and then transfer it to a remote cloud server. The collected data can be displayed to users through a web-based application located on a cloud server. When an emergency is detected, the WE-Safe node is able to alert the user via a mobile application. The proposed network system has been tested outdoors on the Monash University campus. The gateway node is located inside the laboratory, near the window on the second floor. When the wearable WE-Safe node is taken to outdoor on campus, in an environment similar to urban areas, the network can cover 520 m. Experimental results show that the LoRa security monitoring network can work reliably with energy harvesting.

4.3 Adoption of Energy Harvesting Powered LoRa

The aforementioned cases are all energy harvesting powered LoRa / LoRaWAN, which has proven the potential of the systems for smart city applications. The variety of energy harvesters that can be used to power LoRa networks indicates promising potential for large scale implementation of energy harvesting powered LoRa networks for different smart city applications. Apart from the mentioned applications, other potential applications of LoRa / LoRaWAN systems using energy harvesting include smart grids, smart parking, optimised driving and walking routes, energy radiation measurements, measurements of nuclear power station radiation, weather adaptive street lighting, smart waste management, structural health monitoring, fire detection and so forth [72].

It is also worth noting that there are several energy harvesting powered short-range wireless technologies that can be easily converted into long-range wireless technologies, which provides more possibilities for smart city applications. For example, the strain energy harvesting powered ZigBee wireless sensor nodes [37] that uses the charge management circuit and energy-aware approaches with an energy-aware programme as reviewed earlier [61] can be easily converted to a LoRa wireless sensor node by simply replacing the ZigBee transceiver by a LoRa transceiver.

5 Conclusion

The realisation of smart cities requires the cities to have the ability to collect data by leveraging wireless sensing solutions. Power source of wireless solutions that conventionally relies on batteries has always been the bottleneck for their widespread deployment that is low maintenance and sustainable for long-term operation. Fortunately, there is an alternative method to power wireless sensing systems by harvesting energy from the ambient environments as the power source. A complete energy harvesting powered wireless sensing system consists of an energy harvester, a power management circuit and a wireless sensor. All these elements are equally important for the system to operate optimally.

For the design or selection of energy harvesters, it is first necessary to identify the energy sources that are available in the environment. Given that smart cities are about the living quality of people, harvesting energy sources that are directly linked to the presence of human would be beneficial in terms of powering up the sensors in locations that matter. One of the most abundant energy sources is kinetic energy from human activities, running vehicles, in-pipe water flow and airflow. Harvesting kinetic energy in urban environments can be achieved via different mechanisms. Popular methods include using piezoelectric transducers and electromagnetic mechanism. Piezoelectric based energy harvesters are usually solid-state devices, which gives them an advantage in terms of robustness. Therefore, this type of energy harvester can be embedded under road surfaces or floor tiles to harvest energy from direct forces applied onto those locations. However, their output power is usually lower than hundreds of milliwatts under usual operating conditions. Their electromagnetic counterparts especially those that use electrical generator are able to produce power of more than hundreds of milliwatts but the devices are usually larger and involve rotary parts, which may limit their deployment to specific applications. Given that the average power consumption of wireless sensor nodes are only a few milliwatts, many research efforts have been dedicated to piezoelectric based energy harvesters due to their self-contained power generation capability and simplicity of structure. Some innovations such as frequency up-conversion and force amplification are particularly suitable for wearable piezoelectric energy harvesters to increase the output power without requiring the wearers to exert extra effort.

A power management circuit consists of three main parts, namely the voltage conversion, MPPT circuit and charge management circuit that work cohesively to manage and condition the harvested energy to power up wireless sensors. In terms of the voltage conversion, the AC to DC or rectifying circuit requires particular attention to allow energy to be transferred from energy harvesters to wireless sensors via the power management circuit. An adaptive self-configurable rectifier that switches its rectifying topology according to the voltage from the energy harvester allows the power management circuit to operate over a wider range of input than an ordinary circuit with just a single fixed rectifying. The MPPT circuit needs to be able to determine the MPP of energy harvesters swiftly since the energy that can be harvested may only last for a very short period of time. An innovative way is to determine the voltage ratio that corresponds to the MPP of energy harvesters directly from the charging voltage profile of a smoothing capacitor where it does not need other measurements such as power from the previous cycle or open-circuit voltage before the MPP can be determined as in other conventional MPPT methods. The charge management circuit plays an important role in allowing the energy transferred from energy harvesters to be accumulated efficiently in energy storage devices, especially for initial start-up of wireless sensor nodes. The threshold voltages for releasing or halting the energy from the energy storage devices to the wireless sensors need to be properly selected to ensure efficient usage of the harvested energy. The threshold voltages affect the time duration that a wireless sensor can be powered on and the efficiency of the DC–DC converter in transferring energy from energy harvesters to energy storage devices. Apart from hardware solutions, the harvested energy can be better used with an energy-aware software programme where the wireless sensor node will only perform tasks that the available energy is sufficient. This prevents the wireless sensor node to perform tasks that require more energy than what is available, which will be wasted as the wireless sensor node will be turned off before completing the tasks.

Given that a city wide network coverage is required for smart city applications, LPWAN technologies are require for the wireless network. LoRa is found to be an ideal candidate for the implementation of energy harvesting powered wireless sensor networks in smart cities. Some of the attributes of LoRa technology that make it suitable for the purpose include long range connectivity, low power, low cost, good reliability and high scalability potential. Several prototypes from the academia and commercial products that are available on the market show promising performances of energy harvesting powered LoRa sensor networks. Furthermore, some established techniques or sensor node designs for energy harvesting powered short range networks can be easily adopted in the design of energy harvesting powered LoRa based wireless sensing systems.

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