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A Review of Energy Harvesting in Localization for Wireless Sensor Node Tracking

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ABSTRACT The localisation and positioning in Wireless Sensor Node (WSN) are prone to tracking loss because of battery depletion resulted from high power consumption. Considering this, Energy Harvesting (EH) is a significant factor to ensure the sustainability of WSN trackers. Therefore, the key objective of the paper is to review the existing EH approaches, specifically for WSN trackers. An overview of WSNs including the underlying wireless communication technologies is initially presented. We compared the communication range, data rates, power consumption and also the cost across wireless technologies used for WSN. This paper further discussed the localisation and positioning techniques using the Global Positioning System (GPS) and other types of sensors exploiting signal parameters like Received Signal Strength Indicator (RSSI) and Angle of Arrival (AoA). Subsequently, we reviewed the energy harvesting approaches in terms of power density, efficiency and also highlighted their advantages and disadvantages. The EH components such as energy storage and energy-combining circuit for active monitoring are presented as well. Finally, this paper outlined the key challenges and future regards EH for WSN.

INDEX TERMS Energy harvesting, piezoelectric, solar, hybrid energy, boost converter, GPS tracker device.

I. INTRODUCTION

In recent years, advanced microelectronics engineering has seen an unprecedented rise in the number of ultra-low power WSN and devices [1]. The constant growth of sensor systems has caused the upsurge of various utilisations, ranging from systematic health tracking to industrial process control [2], [3]. Compared to wired technology, wireless technology presents many advantages, including flexibility and sensor placement at positions where a wired sensor cannot cover. The wired framework may reduce cost and time, but will not fix concerns like separation. Some examples of WSN-based mechanisms are a Bluetooth device linked to the chest band for transmitting individual heart rate data to a treadmill, and a portable electrocardiograph (ECG) for linking human heart movement to a doctor's display panel. In addition, the ZigBee wireless modules, equipped with a smart meter, are used to monitor energy usage in households or industries and provide customer feedback on the decision-making process [4]. Beyond that, WSN applications are deployed in structure surveillance, defence, location monitoring, and radio frequency detection (RFID). One of the core challenges in WSN deployment is the preservation of network survivability, which eventually leads to high usage. Power consumption is essential in the WSN application control protocol [5], [6]. When a WSN tracker is exhausted, it will be disconnected from the network, affecting the application's performance. Since WSN mostly operates on batteries with a short lifespan, it is crucial to advocate using WSN supercapacitors technology to store the energy from EH sources, depending on the availabilities of the sources. By relying upon the extracted sources, the lifespan of batteries can be prolonged, hence allowing WSN to sustain network accessibility and operate reliably

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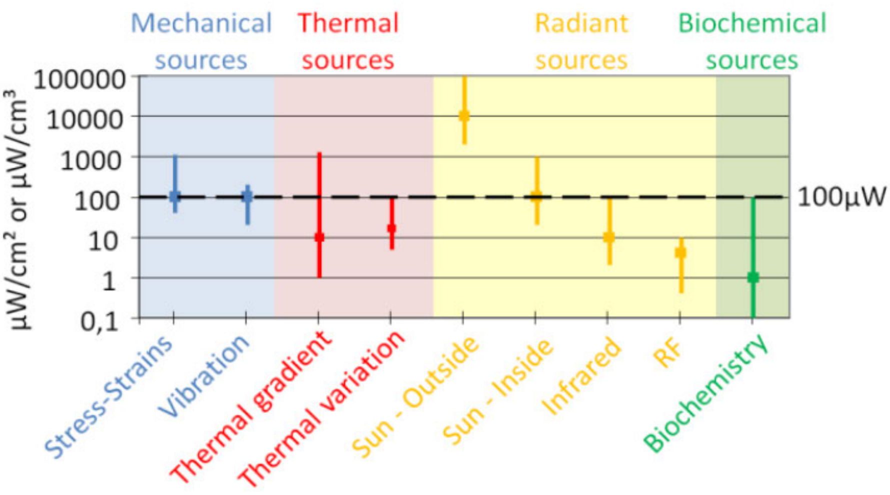

FIGURE 1. **Ambient energy power source before conversion [7].**

for several years before battery replacement. Accordingly, EH strategies have been previously studied as a guide to WSN tracking energy supply technologies. Mechanical energy (vibration or friction), thermal energy (heat), radiated energy (solar and infrared radio frequency (RF)), chemical energy, and nuclear energy are among the common energy sources in our climate. It should be noted that each of the EH streams has different energy densities. Figure 1 shows the energy density breakdown before the conversion. The selection of ambient energy is based on the sensor's environment and applications. Relatively, radiant sources perform better outdoors than indoors (i.e. solar power [7]). However, radiant sources for object tracking settings pose a problem when WSN is in a dark area. Subsequently, the combination of solar and vibration energies offers WSN trackers the most prospective EH solutions when WSN is connected to a moving object (e.g., a car or a horse).

WSN has comprised hundreds to thousands of nodes with limited processing capacity and minimal memory. Although the sensors can be implemented in different environment, the low battery life still poses a challenge in node distance estimation. Localisation is essential for different sensor systems for tracking areas and capturing critical data for specific purposes. Ideally, implementing position sensor should be low in cost and the precision of distance estimation should be high in scores. GPS tracker is a simple form of positioning in direct sight [8], habitat monitoring [9], [10], medical diagnostics [11], [12], and object tracking [13], [14]. Target sensor monitoring typically involves trajectory approximation of one or more moving objects based on partial knowledge, such as GPS coordinates, acceleration, and sensor direction [6], [15].

Most of the researchers have concentrated on GPS-free WSN monitoring via specific algorithms, including range-based or range-free node tracking techniques [16], [17]. Even though these strategies can reduce power consumption and extend WSN service with limited sensor usage, the proposed work still lacking in precision and has high complexity. GPS tracking device generally relies on the sensitivity of the GPS sensor for direct location and high precision. However, little attention has been paid to the integration of wireless GPS sensor tracker and EH technologies for prolonging the WSNs [9], [12]. This paper, therefore, suggested the designation of a WSN monitoring system through the combination of GPS with EH to maintain the energy of sensor node and integrated circuit (IC) architecture, consequently reducing the size of the device and power consumption.

Integrating solar-based and mechanical vibration-based sources would lead to high-performance measurements in system power usage, position precision, and life cycle optimisation. Table 1 summarises the comparisons of this paper with related works. According to authors in [18] focused on incorporating composite EH from three separate sources, while other works focused on a single energy storage source1. In relation, the works in [19] and [20] have been devoted to performing solar and vibration EH technologies, respectively. Even though the works in [9] and [20] targeted the same EH technologies and performance metrics, they differ in the implementation and also output reliability. Additionally, the works in [12] and [18] have emphasised radiated sources and were the only research that incorporated success metrics.

This paper provides a compact assessment of GPS-integrated EH technology, environmental and application, and explicitly reviews the vibration along with solar energy harvesting technologies. The contributions of this paper are fourfold:

- An overview of WSN including a comparison of supported wireless communication technologies
- WSN localisation and positioning techniques via GPS and sensor-based
- Tabulated comparison of existing WSN trackers with EH technology

TABLE 1. Comparison the current review paper with previous reviews.

Reference / Year of publication	Tracking system using GPS integrate with EH			Comparison the Performance Metrics		
	Mechanical (Vibration)	Radiated (Solar)	Thermal (Heat)	Power \ Consumption	Localisation accuracy	prolong operation lifetime
[19] / 2019		✓		✓		
[9] / 2018	✓					✓
[?] / 2018	✓			✓		✓
[12] / 2018		✓			✓	
[18] / 2016	✓	✓	✓		✓	✓
This paper	✓	✓		✓	✓	✓

- Energy harvesting approaches comprising energy storage and energy combining circuits

This rest of the paper is organised as follows. Section II summarises wireless sensor networks, including the underlying communication technology. In Section III, we discuss WSN localisation and positioning, which are GPS and sensor-based. Section IV reviews EH for WSN such as energy harvesting approaches, energy storage, and energy combining circuit. Section V highlights the key challenges and future works, followed by a conclusion in Section VI.

II. OVERVIEW OF WIRELESS SENSOR NETWORK (WSN)

WSN is a sensor node that transmits wireless signal data from an area to the administration centre or control centre. Technically, WSN is deployed at the infrastructure or base station to gather data through a single sensor node from a particular location. The region sensor node adequately gathered all knowledge and specific data of the environment for further analysis [21]. On another note, WSN can serve as an ad hoc wireless network as well. Figure 2 shows examples of WSN usage across various industries.

WSNs incorporated several features such as compact sensors, sensor integration, data collection, and wireless networking technologies. Many sensor network design applications are for sensor measurement, tracking, and large-scale analytical applications [22]. The military use network sensor nodes for transmitting enemy information in the battlefield and trans-border early warning system [23], [24]. Correspondingly, distance calculation by each node is critical for these kinds of applications where an error might affect the defence of a country.

The category of sensor node implementations is according to the required coverage and performance (i.e. data speed or latency). Stationary installation in a house can highly locate the needed coverage of a particular use case, while container tracking scenario requires global service coverage. The 3GPP systems apply in cases of major geographic scope requirements and medium to high performance standards. With the latest ranges of features offered in LPWA applications, 3GPP technologies take an enormous leap to cover low-cost and low-performance segments.

Table 2 outlines the variations in cellular network infrastructure requirements. A Bluetooth transceiver module uses a 2.4GHz frequency and has 250mW of total power consumption. The drawback of Bluetooth is the small communication range for transmitting and receiving data (i.e. between 10m and 50m). Likewise, a Wi-Fi transceiver module has 835mW of total power consumption with increased access time, and a contact range of only 100m. On the other hand, the ZigBee transceiver module uses the frequencies between 868MHz, 915MHz, and 2.4GHz, and has 36.9mW of total power consumption with a contact range of 100m as well. The downside with ZigBee is that it demands a clear line of sight (LoS) between the sensor node and the coordinator. Meanwhile, General Packet Radio Service (GPRS) uses frequencies between 900MHz and 1800MHz, and has 560mW of average power consumption with a wide communication range of 1km to 10km.

NB-IoT is another transceiver module with excellent communication range, though it only carries 220mW of total power usage through LTE-based minimum power consumption technology. Meanwhile, the LoRa transceiver module uses frequencies between 869MHz and 915MHz, and has low power consumption with broader contact range. LoRa is suitable for drainage, smart grids, environmental conservation, and lighting power. Unlike LoRa, the SIGFOX transceiver module has a more excellent contact range, but higher power consumption. This paper emphasises LoRa instead to create a wireless GPS sensor node tracker because of its power consumption (i.e. 100mW) and communication range (i.e. 5km).

III. WSNs LOCALISATION AND POSITIONING

Localisation plays an essential role in various sensor applications for mapping regions and gathering critical data, where the precision of distance measurement is significant. Localisation analysis is locating and approximating a node. GPS is one of the simple placement techniques, but requires a direct LoS [53]. Missile guidance and medical diagnostics are examples of systems that adopted wireless sensor positions for tracking. In this section, positioning problems, with and without GPS, are discussed pertaining on location accuracy.

Table 3 shows the comparisons of the wireless sensor node for localisation and positioning. In 2018, most researchers

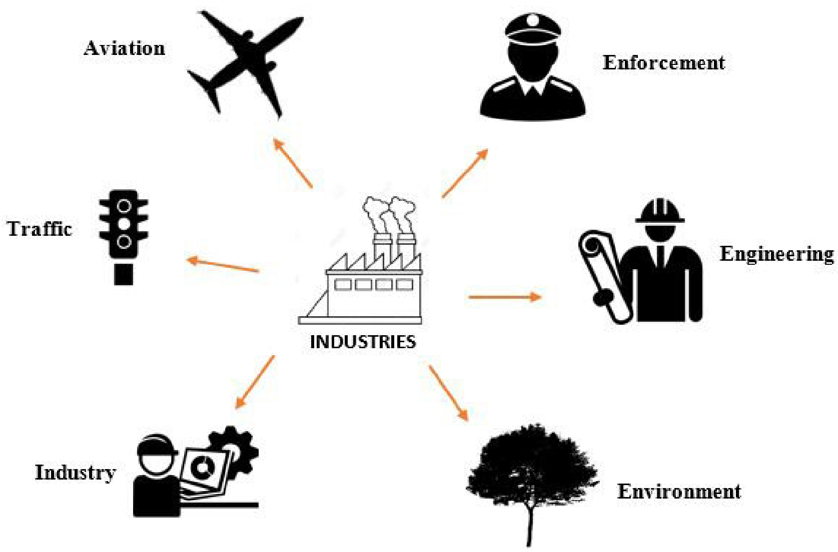

FIGURE 2. Wireless sensor network application.

TABLE 2. Comparison between several wireless network technologies.

Wireless technology	Frequency (MHz)	Communication range (m)	Data Rates (kbps)	Power consumption	Cost
Bluetooth [25]–[28]	2400	10	1000	Ultra Low 10mW	Low
WiFi [28]–[34]	2400 / 5000	100	11000 - 54000 / 150000	High 835mW	High
ZigBee [35]–[37]	868 / 915 / 2400	100	20 / 40 / 250	Low 36.9mW	Low
GPRS [14], [38], [39]	900 - 1800	1000 - 10000	Up to 170	Medium 560mW	Medium
Telemetry RF [40]	433 / 915	500 - 1000	50	Low 35mW	Medium
LoRa [41]–[49]	433 / 869 / 915	5000 (Urban) 20000 (Rural)	50	Low 100mW	Low
SigFox [46], [50], [51]	868 / 915	10000 (Urban) 40000 (Rural)	100	Low 122mW	Medium
NB-IoT [46], [52]	4G-LTE (699 - 2200)	up to 1000 (Urban) 10000 (Rural)	250	Low 220mW	Medium

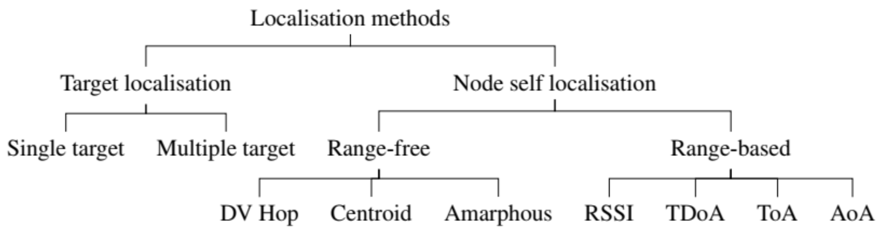

FIGURE 3. Localisation methods taxonomy [54], [55], [67].

used GPS technologies to identify the location of the Tx node via the LoS toward space or satellite. The Tx node sends the location coordinate to the receiver node, and the GPS receiver needs at least three satellites to identify the location coordinate. This method, however, has a limitation when the Tx node is covered in shadows or under a building. In [8], the proposed device harvests electric power using air bulbs installed in the sole of a shoe to trigger a series of micro-turbines connected to small DC motors. A 75kg test subject wore a prototype combat boot and produced an average continuous power on the order of 10s of mW while walking at 3.0mph. In [12], the proposed device comprising a GPS tracker, temperature sensor, and a force sensor. The device is miniaturised using nanotech and implanted in the teeth of a child. When the temperature sensor reached beyond the normal range, it sent an alert message to the parents' mobile number. According to [54], localisation study has become a central attraction for tracking objects in the era

TABLE 3. Comparison of wireless sensor node for localisation and positioning.

Related work	Year	Category	Localisation technique	Advantage	Disadvantage
[57]	2020	Sensors technology	hybrid (RSSI and AoA)	- The machine applied simulation findings validate the excellent efficiency of the proposed approach in solving the localisation issue efficiently in variety of scenarios for hybrid RSS-AOA measurements.	- To solve localisation issues using simulation, which is not implemented yet.
[56]	2019	Sensor technology	RSSI	- an equal-arc triangular beacon node layout model is established - the proposed work increases the average location accuracy of the equal-arc triangulation layout model by 81%, 54%, and 48%	- Need at least a four-receiver node - Additional cost for the receiver node compares with the triangulation method
[55]	2019	Sensors technology	RSSI	- Localisation using trilateration and multilateration - Low power consumption - Able to locate the target sensor	- Efficiency is less than 60% for multilateration and 50% for trilateration
[19]	2019	GPS Technology	GPS Coordinate	- Efficiency around 10m radius - Low power consumption - Using solar energy harvesting to prolong tracking	- Using RF (UHF) for communication medium and distance below 1 km radius - Need line of side to the spaces
[54]	2018	Sensors technology	RSSI	- Low power consumption - Able to locate the target sensor	- Localisation efficiency is low for triangulation method
[58]	2018	GPS Technology	GPS Coordinate	- Localisation efficiency up to 10m radius - Low power consumption - Using solar energy harvesting to prolong tracking	- Using RF (UHF) for communication medium and distance below 1 km radius - Need a line of side to the spaces
[12]	2018	GPS Technology	GPS coordinate	- Location efficiency up to 10m radius - Using thermo-electric energy harvesting to prolong tracking	- High power consumption - GSM modem and using SMS for sending data to the monitoring software - High cost in sending data because of chargers per SMS - Need line of side to the spaces
[8]	2018	GPS Technology	GPS coordinate	- Localisation efficiency up to 10m radius - Using micro-turbine energy harvesting to prolong tracking	- High power consumption - GSM modem and using SMS for sending data to the monitoring software - High cost in sending data because of chargers per SMS

of a new global economy. The object environment has a substantial effect on accuracy offered by the localisation algorithms. Correspondingly, the proposed system in [54] can be deployed for a small low-cost and low-power LoRa tracking device with no GPS dependency, improving the localisation even when the Tx node is covered in shadows or under a building. Nevertheless, this method needs at least three Rx nodes to identify the location of the Tx node. The authors in [19] proposed an energy harvesting architecture and energy management logic to design the wireless sensor nodes for animal tracking, specifically pink iguana, in the Galapagos Island. Wireless networks have been a focal point for smart environments and smart monitoring because of their low power consumption with long-range connectivity [55]. The wireless sensor module in [55] utilised LoRa with 868MHz frequency. The authors claim that the multilateration method is more accurate than trilateration. The results demonstrated that the localisation accuracy in the Tx node increases as the number of Rx nodes rises. Contrariwise, the authors in [56] proposed an equal-arc trilateral localisation algorithm based on the received signal strength indicator (RSSI) to increase measurement precision. The algorithm adopts the Kalman filter to extract the data collected from the best communication range. According to the authors, an optimal communication distance can be identified and satisfy the application requirements. The proposed work increases the average location accuracy by 81% compared with the traditional square beacon model. The authors in [57] addressed the target localisation problem in 3D wireless sensor networks via a hybrid system that merges received signal strength with the angle of arrival measurements, and proposed a semi-definite relaxation and second-order one relaxation-based estimator. Theoretical analysis and computer simulations demonstrated that the proposed localisation method performed better over the existing ones.

A. GPS TECHNOLOGIES

According to [53], GPS is the most popular outdoor positioning technology for sensors. Place finding is gaining mobile client (MC) location information to gather reference positions within a pre-defined area. Position observations use many terminologies, such as position direction, geolocation, location sensing, and direction [59]. The positioning method is a system estimation of an object's position. Global Navigation Satellite Systems (GNSS), such as GPS units, have been used in a broad range of applications, including tracking and asset management systems, transport navigation and guidance, telephone network synchronisation, and geodetic surveying. Although GPS sensors are widely preferable for outdoor positioning, the systems may encounter indoor and

TABLE 4. Comparison of the GPS tracker devices.

GPS tracker	Geo-Trax [62]	TK-102B [61]	HidnSeek [63]	iTAG [64]
Communication modes	LTE	GSM/GPRS	SigFox	Bluetooth
Distance communication	1-10km	1-10km	1-10km	75m
Operation band	900-1800MHz	850-1800MHz	433MHz	2.5GHz
Location technology	GNSS	SIRF3	ublox MAX M8	-
Location accuracy	2.0m	5.0m	2.0m	-
Operating voltage	7-32V	5V	5V	3V
Power consumption				
- Deep sleep	<3mA@12V	10mA@5V	0.21mA@5V	0.048mA@3V
- radio-active sleep	25mA @ 12V	-	-	-
- Active tracking	50mA @ 12V	-	4.46mA @ 5V	-
Backup battery	3.7V 1000mAh	3.7V 800mAh	3.7V 460mAh	3V 210mAh
Dimensions	94x53x20mm	64x46x17mm	85x1.88x15mm	51x31x11mm
Weight	80g	50g	48g	8.5g

underground settings issues as these areas have the satellite limitation [60].

Table 4 provides a comparison of the existing GPS tracker units. The function of the GSM/GPRS transceiver module is for transmitting system data to the server. As seen in the communication modes of Table 4, GSM/GPRS displays a high power consumption of 10mA in standby mode [61]. LTE and SIGFOX, however, showcase a low power consumption of less than 3mA and 0.21mA, respectively [62], [63]. The lowest usage belongs to Bluetooth, with 0.048mA of power consumption [64].The localisation technologies used in Geo-Trax, TK-102B, and HidnSeek is GNSS, SIRF, and ublox MAX M8, accordingly. The selection of technologies has an advantage in the accuracy of localisation, as demonstrated by TK-102B with its highest radius up to 5.0m. Contrarily, the iTAG device utilised sensor technology to identify the location coordinates based on Bluetooth signal strength and RSSI.

B. SENSORS TECHNOLOGIES

Figure 3 presents the taxonomic view of the existing methods in localisation methods. Localisation can be broadly divided into two sub-categories, namely target localisation and node self-localisation. Accordingly, target localisation can be classified into single target and multiple target locations, while node self-localisation can be categorised into range-free and range-based approaches [13], [55]. Self-localisation node serves an integral part in node positioning. The benefits of self-localisation node include cost-effective, quick deployment, and low power consumption [65], [66]. A range-free algorithm is a tool for calculating a node's position by using the conjecture techniques of centroid, DV-hop, and geometry distance between the transmitter and the receiver. The range-based algorithm, on the other hand, involves techniques such as receiving signal intensity indicator (RSSI), time difference of arrival (TDoA), time of arrival (ToA), and angle of arrival (AoA).

Table 5 shows the distinction between the range-based and range-free algorithms for a GPS-free node sensor location. As tabulated in Table 5, the RSSI technique requires no specialised hardware and can be cost-effective with possible attenuation. In contrast, the AoA technique is costly as it requires a multi-antenna array or motorised antenna [68]. ToA and TDoA techniques exhibit average cost with low attenuation, and require advanced localisation hardware. Algorithms are essential for position computation to classify sensor node location. There are three primary node location and positioning algorithms, namely trilateration, triangulation, and multilateration. As for the range-free techniques, no specific hardware is needed, but the attenuation is high to the point of affecting the positioning precision.

C. KEYS ISSUES ON EH

The fundamental issues with wireless GPS sensor node tracker are high power consumption and short-lived batteries. WSN tracking with GPS still has a chief benefit, a position of efficiency for object tracking and outdoor applications. There have been several discussions on integrating WSN tracking with GPS receiver for low-power consumption. The goal sensor is a battery that provides node control and can run reliably for several weeks or months before depletion. Conventionally, the batteries must be changed or recharged for long-term operation or monitoring. Unfortunately, this is a problem for compliance applications, especially on whether to charge the battery regularly or within a week since it includes personal protection and classified operations.

As seen in Table 6, researchers have shown interests in GPS-based WSN integrated with EH technology for the sake of network connection sustainability and real-time monitoring. Lavanya R *et al.* (2018) adopted the thermoelectric EH source for autistic child tracking and human body temperature monitoring [12]. Meanwhile, Haluk Akay *et al.* (2018) examined the micro-turbine embedded GPS tracker systems as EH supply [8]. They created a GPS tracker for military boot, and utilised supercapacitor and battery as dual-energy storage for the GPS tracker. This is opposite from Loreti *et al.* (2018, 2019) developed a WSN to map and control the pink iguana, a newly discovered species living in the remote location of the Galapagos Islands [19], [58].

The lifespan of a battery can be extended by using ambient sources and converting them to charge the battery and energy storage. Some potential energy sources are, but not limited to, light [79], [80], kinetics [8], [9], [81], [82], acoustics [83], [84], thermal [12], [85], wireless [86], [87], chemical,

TABLE 5. Comparison of WSN Localisation methods for sensor technology.

	Principal of Operation	Special Hardware	Attenuation problem	Cost
Range-based techniques				
RSSI [55], [69]–[73]	Signal strength measurement	Not required	High	Low
AoA [68], [73]–[76]	Angle of signal arrival	Required	Medium	High
ToA [17], [68], [70], [74], [76], [77]	Time of arrival	Required	Low	Medium
TDoA [16], [17]	Time difference in propagation at different points	Required	Low	Medium
Range-free techniques [78]				
DV Hop	Heterogeneous network that consists of sensing nodes and anchors	Not required	High	Low
Centroid	Use transmit beacons containing (Xi, Yj).	Not required	High	Low
Amorphous	Takes different approach from DV-Hop for average single hop.	Not required	High	Low

TABLE 6. Energy harvesting for Wireless Sensor Node localisation and tracking.

Author	Method	Energy Harvesting	Energy Storage	Wireless Technology
Lavanya R. et al. (2018) [12]	- Tracking autism children using GPS - Monitor human body temperature - Force sensor (biometric sensor)	Thermo-electric	Battery	GSM modem (SMS)
Haluk Akay et al. (2018) [8]	- Electric power harvests using air bulbs and connected to the micro-turbine. - The GPS tracker fits on the right foot of the combat boot prototype.	Micro-turbines	Super-capacitor & battery	GSM modem (SMS)
Loreti et al. (2018,2019) [19], [58]	- To monitor the position and activity of the pink iguana - The operations of the sensor node are the following: (i) acquisition GPS position and (ii) retrieval of sensors values, (iii) storing all information and (iv) data transmission through the gateway.	Photovoltaic	Super-capacitor	RF (UHF)

wind [39], [81], [84], [88], and hybrid [89]. Light is the recurrent source for environmental EHs, where the solar cells harvest the energy from the sunlight. The development of ultra-low power consumption for WSN is considered an integral part of the electronic system design flow. Most researchers concentrated on maximising battery life and avoiding excessive removal or recharging of batteries [90] to reduce power consumption. However, the size of a wireless GPS sensor node appears to be unsuitable for an animal tracker or compliance applications, as they are often large in scale. Alternatively, the researchers introduced the EH architecture and associated energy management logic. They also addressed the effect of packaging on sensor efficiency and the minimal energy available on GPS monitoring.

IV. ENERGY HARVESTING FOR WSN

A. ENERGY HARVESTING APPROACHES

EH is a technique that absorbs un-utilised light, kinetic, thermal, wireless, chemical, wind, acoustic, hybrid, and other renewable resources and transforms them into usable electrical energy capable of delivering power to wireless sensors for sensing or actuating functions. Several researchers have explored on how to harness energy from small-scale or low-power electronic devices [83]. Figure 4 shows the device-induced electricity-induced EH technologies. There are eight divisions of currently discovered energy sources for energy harvesting, and several of these sources are further separated into many other sources, each with a distinct

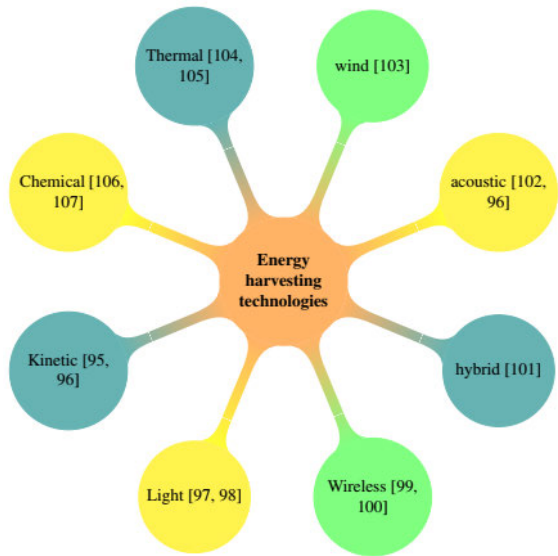

FIGURE 4. Energy harvesting technologies.

technique. The classification facilitates researchers to use the right method for their study. Light offers two harvesting choices, i.e. natural light, such as sunshine, and artificial light, such as street lamps. There is piezoelectric vibration in kinetic, electrostatic electron movement, and electromagnetic magnetic movement in the electric field.

Figure 5 illustrates the view of the new Vibration Energy Harvesting (VEH) [7], [91]: time-related VEH sector and

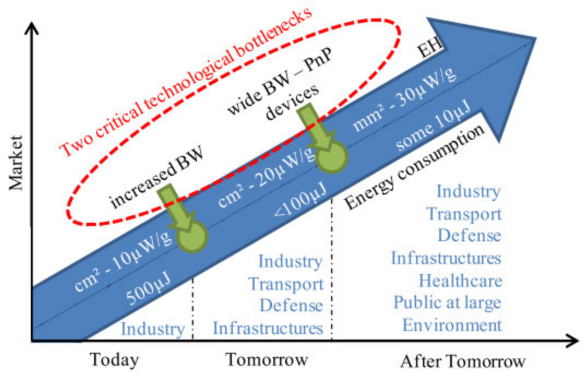

FIGURE 5. Vibration Energy Harvesters - Perspectives [7], [91].

two bottlenecks connected to the operating frequency bandwidths. According to this pattern, the existing VEH remains adequate for the industry. The best way to extend and dominate the new market is to maximise the operating frequency bandwidths and create plug-and-play applications.

Table 7 provides a list of resources harvested from various sources. Each EH technique shows the power density and conversion efficiency, and the expression is in extracted energy per unit volume, area, or mass. The control units are watts per square centimetre, W/cm^2, and watts per cubic centimetre, W/cm^3. Efficiency conversion is the ratio of extracted energy to harvest energy supply. Typically, energy conversion efficiency varies from 0 to 100%. Photovoltaic has the highest conversion as the efficiency rate approaches 100% in peak and natural settings, followed by radio-frequency with a conversion efficiency rate of 50% and wind efficiency of 5%. Other harvesting techniques allow less production, which is inadequate for commercial use. Nonetheless, the techniques are considered for limited power devices and certain applications.

Concerning the geographic region of Malaysia, it is reasonable to use solar as an EH technique, as a generous amount of sunlight is generated throughout the year compared with the four-season countries. Moreover, the high performance generated can overcome the high installation costs and effectively deliver long-term benefits to consumers. This paper presented a combination of piezoelectric with solar energy harvester to produce a hybrid EH technology. The advantages of selecting piezoelectric as a joint-energy harvesting device are simple structure and high voltage performance. Proper installation and calibration can resolve issues concerning the thin-film fragile state. Accordingly, the EH system would supply the required energy to a portable GPS sensor tracker. The EH system would incorporate a hybrid energy storage system such as a lithium battery and supercapacitor. The supercapacitor will act as an energy shield until charging is begun.

B. ENERGY STORAGE

Energy storage includes three different types: batteries, supercapacitors, and thin-film batteries. Batteries are usually made of advanced power-supply technologies. Key metrics of the energy storage elements to be considered when choosing EH applications include output voltage rating, efficiency, self-discharge current, total load-discharge cycles, energy density, and power density. The function of power converter is to provide power to the output voltage of the energy buffer in EH. The number of load-discharge cycles determines the reliability of an EH system. Supercapacitors have greater power density and lifetime than batteries, and can be utilised to counter short-term power surges [101]. Many sensor platforms with harvesting capabilities deployed supercapacitors as the energy storage system, either by themselves [102], [103] or with batteries [104], [105]. Over the years, battery technology has been evolved to the thin-film batteries. Table 8 defines various efficiency metrics of energy storage component in WSNs.

Battery systems customarily apply two distinct battery types, nickel-metal hydride (NiMH) and lithium-ion (Li-Ion) batteries. Some early high-powered EH systems use **NiMH battery** technology to recycle energy from regenerative braking in electric vehicles. The NiMH batteries are composed of a rare earth metal hydride as the cathode side, nickel-metal as the anode side, and potassium hydroxide as the electrolyte side. These batteries have a 1.2V output voltage, and use a continuous current or voltage source. The charging process is completed either by measuring battery voltage or temperature. The significant advantage of NiMH batteries is that they are very safe to use, as overloading would not pose a risk or security threat. Conversely, the major drawback of NiMH batteries is the comparatively high self-discharge rate, which losses around 5% of power per day [106].

The **Li-Ion battery** is the primary power source for portable electronic devices and is suitable for EH applications. This form of the battery comprises lithium cobalt oxide ($LiCoO_2$) or lithium manganese dioxide ($LiMnO2$) as the cathode terminal, lithium salt (e.g. lithium hexafluorophosphate ($LiPF_6$)) as the electrolyte, and carbon as the anode terminal. The peak voltage is 3.6V with an over-voltage and under-voltage threshold of 4.2V and 2.5V, respectively [107]. The advantages of using Li-Ion batteries in EH applications include a wide range of strengths, shape factors, and relatively high capacity and power efficiency. The performance of commercially available single-cell Li-Ion batteries can be as low as 40mAh, making them suitable for WSNs needing small factor batteries. The drawbacks of these batteries. However, the drawbacks of these batteries are battery protection, which requires a special circuitry to avoid the overloading of batteries. The specific charging profile comprises constant charging to full charging power and battery life extension. The battery cannot be charged if the cell temperature is over $50°C$ or below $20°C$. Li-Ion battery-powered devices have dedicated circuits to regulate battery voltage for over-voltage, under-voltage, over-current and over temperature conditions.

Electric Double Layer Capacitor (EDLC) is another term for supercapacitors or ultra-capacitors [108]. The **supercapacitors** are designed as conductive elements with two rigid

TABLE 7. Power density and efficiency of energy harvesting technique.

Energy harvesting technique	Power density	Efficiency	Advantage	Disadvantage
Photovoltaic [79], [80]	Outdoors(direct sun): $15mW/cm^2$ Outdoors(cloudy day): $0.15mW/cm^2$ Indoors: $< 10uW/cm^2$	Highest: 321.5% Typical: 251.5%	- High power output - suitable large scale - clean energy - Cheap in the long run	- It does not work at night - Expensive for installation and maintain - Depend on the environment - Geographical uniform
Thermoelectric [12]	Human: $30uW/cm^2$ Industrial: $1to10mW/cm^2$	0.1% 3.0%	- No moving part - Scalable - Durable	- Very low conversion efficiency - Low output voltage
Pyroelectric [85], [92]	$8.64uW/cm^2$ at the temperature rate of $8.5C/s$	3.5%	- No moving parts - Long lifespan - Potential for the human body wearing applications	- Low energy - Higher cost - Low power output (about $40uW/cm^3$) - Limited usage due to higher temperature gradient requirements - Power output depends on thermal gradient conversion efficiency
Piezoelectric [8], [9], [81], [93]	$250uW/cm^3$ $330uW/cm^3$ (shoe insert)	-	- Simple structure - No external voltage source - Compatible with MEMS - High output voltage - No mechanical constraints needed	- Thin films have low coupling - Poor mechanical properties - High output impedance - Charge leakage - Low output current
Electrostatic [94]–[96]	50 to $100uW/cm^3$	-	- Easy to integrate with MEMS - High output voltage	- Mechanical constrains needed - External voltage source or pre-charge electric needed - High output impedance
Electromagnetic [87], [97], [98]	Human motion:1 to $4uW/cm^3$ Industrial: $306uW/cm^3$, $800uW/cm^3$	-	- No external voltage - No mechanical constrain need - High output current	- Difficult to integrate with MEMS - Poor performance in micro-scale - Low output voltage
RF [86], [99]	GSM 900/1800MHz: $0.1uW/cm^2$ WiFi 2.4GHz: $0.01uW/cm^2$	50%	- Works in dark locations also - Provides power on demand and even in mobility - It can work as secondary battery while on travel	- Human health - Limitation of size and shape - Low output voltage - Hing losses
Wind [81], [100]	$380uW/cm^3$ at speed of $5m/s$	5%	- Can be found singular - Potentially infinite energy supply - No harmful gases produced	- Manufacture and implementation costly - Spoils the countryside
Acoustic [83], [84]	$0.96uW/cm^3$ at 100dB $0.003uW/cm^3$ at 75dB	-	- No external voltage - No mechanical constrain need	- Difficult to integrate with MEMS - Poor performance in micro-scale - Low output voltage

electrodes, isolated by a thin electrolyte substance (e.g. activated carbon). Owing to the large specific area (i.e. area per unit volume) of the electrode material and the small spacing (few Angstroms) between the charging layers, supercapacitor strength can be increased. The primary advantages of supercapacitors are high-power density, nearly infinite number of charging cycles, improved stability at high and low temperatures, and low equivalent series resistance (ESR), enabling high discharge speeds. The supercapacitors' self-discharge is like Li-Ion batteries, but is more than thin-film batteries. Inversely, the primary downside of supercapacitors is the reduction of voltage resistance. Since the electrodes are quite the same as each other, an electrolyte material breakdown can occur at voltages as low as 3 V. Meanwhile, for high-voltage applications, two or three condensers are used in series to increase the total voltage rating. Nonetheless, as the number of condensers grows in series, the system will need special circuitry to control voltages through each condenser.

A **Thin-film battery** is from $LiCoO_2$ or $LiMnO_2$, which is sprayed out of the goal. The deposited electrolyte is coated with polymeric materials such as lithium phosphorus oxynitride (LiPON). The material of thin-film battery-anodyne is lithium metal or inorganic. The thin-film battery can provide an output voltage of 4.2V, while the under-voltage is 3V. The battery is stable as it does not pose a safety hazard, and can charge with steady current and voltage. The safety features prevent the battery from damaging, and use circuitry to monitor the battery's over-voltage condition during

TABLE 8. Summarises the various performance metrics of the energy storage elements.

	NiMH [106]	**Li-Ion** [107]	**Super-capacitor** [108]	**Thin film battery** [109]
Max. Output Voltage	1.2V	2.5-4.2V	1.2-5V	4.2V
Recharge cycles	500	100	Millions	5k-10k
Self-discharge	High	Moderate	Moderate	Negligible
Charge time	Hours	Hours	Sec-minutes	Minutes
Physical size	Large	Large	Medium	Small
Enviroment impact	Minimal	High	Minimal	Minimal
Capacity	up to 2200mAH	40-1500mAH	10-100uAH	50-2500uAH
Advantage	- Very safe to use - The overcharge does not lead to cell damage - Higher energy density - Lower cost than Li-ion	- Nearly 100% energy storage - Low self-discharge rate - High energy per unit weight	- Much higher recharge cycle life - High cycle efficiency (>95%) Much longer lifetime compared to batteries - Environmentally friendly - Broader range of voltage and current - Low internal resistance - High performance in low temperatures	- Simple fabrication - Flexible (non-breakable) - High voltage can apply - Required low fabrication temperature ($< 300^oC$)
Disadvantage	- The relatively high self-discharge rate - Lower recharge cycle life - Much lower lifetime	- Lower recharge cycle life - Much lower lifetime - Complicated charge module	- Expensive - Low energy per unit weight - Low per cell voltage - High self-discharge rate - High dielectric absorption	- Expensive

charging and under-voltage condition during discharge. The primary advantage of a thin-film battery is its nearly zero self-discharge. This feature makes them appealing to EH applications where the system cannot be powered for prolonged durations. Because of self-discharge, the battery must minimise the lack of stored energy for long periods. Another feature of the thin-film battery is an increase in charging times relative to the Li-Ion battery. Correspondingly, this type of battery is preferable when replacing the battery is deemed dangerous or prohibitively expensive. The major drawback of a thin-film battery is its limited scale, from 50uAh to 2.5mAh. Because of the battery's minor power, system configuration must operate at low battery capacity.

C. ENERGY COMBINING CIRCUIT

As seen in Table 9, the simplest method of multi-source EH is to gain energy from primary sources and use it as a secondary source to power the auxiliary circuit in the Power Management Unit (PMU) [110]. However, the complementary energy source design does not really incorporate energy from both input sources to supply it to the loop. Additionally, the circuit lacks the maximum point power tracker (MPPT) functionality and requires a maximum EH output feature.

Power ORing's combined circuit is a fast and effective multi-source energy extraction technique, as implemented in [111], [112]. The advantage of Power ORing is that it can support an arbitrary number of EH sources and can perform MPPT independently on its transducer. However, the downside of this technique is the extra power loss because of the diode's forward drop voltage and the size and cost boost of the MPPT circuit.

The voltage level detection technique in [113] is a more complex control system that replaced the Power ORing diode with a voltage-controlled switch to minimise computer power losses. The advantages of this method are no simultaneous energy harvest from multiple inputs and no potential power loss. There is, however, marginal applicability to atmospheric energy sources for volatile variation and voltage level detection approach.

In [114], the linear regulator technique is extended to the current type by linking individual linear regulator output. A single storage system (i.e. SSD) external capacitor is used to store energy and stabilise low-dropouts (LDOs), while no battery function is being utilised. The advantage of this strategy is that it can simultaneously gain energy from several sources via a simple control algorithm. The drawbacks include less productive output limits and a stabilisation problem. Because of the simple circuit and efficient power output for GPS sensor node tracker applications, this research proposed to incorporate a multi-source EH circuit with the Power ORing technique.

Buck-boost converters are widely adopted in energy production to form a similar MPPT impedance scheme. It happens because the converter's input impedance can be conveniently tuned through the frequency control to form a time-average input resistance. The buck-boost converter can utilise a shared inductor scheme to minimise the number of external components required by considering several inputs. Using this topology, the complex controller must allow all inputs to the only inductor, while ensuring each input achieved optimum power transfer. One major drawback is that the method can deviate from a genuinely concurrent energy harvest as the number of input sources increases, with

TABLE 9. Comparison of multi-source energy harvesting combining topology.

Ref.	Topology	No. of EHs	EHs Type	Technology	MPPT	Battery Charg-ing	Peak η
[110]	Complimentary use	2	TEG PZT	HV 0.35um CMOS	No	No	82%
[111]	Power ORing	2	PV Wind	Discreate	Yes	Yes	80% (PV) 85% (Wind)
[112]	Power ORing	2	PV PZT	Discreate	Yes	Yes	85% (PV) 68% (PZT)
[116]	Power ORing	2	PV TEG	Discreate	Yes	No	91%
[113]	Level detection	2	RF TEG	0.35um CMOS	No	Yes	50%
[114]	Linear regulator (LDO)	3	RF PZT PV	0.13um CMOS	No	No	85%
[117]	Shared Inductor	4	TEG PZT RF PV	0.32um BCD	Yes	No	89.6%
[118]	Shared Inductor	3	PZT RF PV	0.18um CMOS	Yes	No	87%
[119]	Shared Inductor	3	TEG PZT PV	0.35um CMOS	Yes	No	58% (TEG) 79% (PZT) 85% (PV)

at least one transducer remains unconnected. This effect is reduced for the larger buffer condenser since it stores energy while the harvester is removed. However, it will affect the MPPT phase open-circuit (OC) voltage setting time, as previously mentioned. Subsequently, a trade-off is made between tracking precision and harvesting performance [115].

V. KEY CHALLENGES AND FUTURE OUTLOOKS

In principle, a sensor must be fitted with low-power transceiver or the battery will undergo rapid depletion otherwise. The critical challenge is to maximise energy usage, since the tracker technically requires a durable power supply. As the amount and the size of sensor networks expand, reparation of exhausted batteries shall be deemed costly and time-consuming [120]. Without long-lasting energy, it would be impractical to execute real-time monitoring of a sensitive object or subject. Therefore, the sensors must be self-powered to avoid network disconnection and allow persistent monitoring [121].

Using a solar panel for EH is a standard practice for green energy and preferably for sensor activities. However, specific applications may not always be practicable for solar EH, and alternative energy sources must be considered [18]. The main issue with solar EH is that the energy can only be provided for some parts of the day, and assuming that the WSN is operating continuously, any received energy should be maintained for night time as well [118]. The challenge is to determine what sort of energy sources can be combined by considering the cost, weight, and viability of devices.

The primary obstacle for hybrid EH is designing a workable energy mix circuit that can combine two energy sources. To date, only a few studies have concentrated on making a range of EH sources for these power systems, while others are dedicated to one form. In addition, energy storage forms ought to be taken into consideration in future works as well. Another practical question that needs to be answered is the feasibility of a hybrid battery, particularly for hybrid energy sources.

VI. CONCLUSION

This paper provided a review on EH approaches for WSN localisation and positioning. It also compared the communication range, data rates, power consumption and also the setup cost of the existing wireless technologies for WSN. Apart from that, the assessment of wireless sensor methods, i.e. with and without GPS, were carefully addressed as well. The comparisons of former techniques in EH were examined besides the energy storage and energy-combining circuit were discussed. The key challenges and future works were also highlighted in the paper.

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