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Super-capacitor based energy harvesting system for Wireless Sensor Node.

V.C. Lokhande* and Y.M. Patil.

Abstract : The present wireless sensor nodes work mostly on battery. There are a few platforms available which perform energy harvesting and use the harvested energy for their operation. While doing so they directly store the energy in the only available power source i.e. battery or super-capacitor. To overcome this problem, the energy harvested is stored in the super-capacitor and used later when solar radiation is not available to drive the circuit. This reduces the dependency on the battery and helps in prolonging battery's life by reducing the charging-discharging cycles. The solar panels will charge both power sources separately whenever there is sufficient output from the solar panels. When the sources are charged it will directly power the node. By doing this the life of the node is increased by many folds and also the health of the battery improved by avoiding futile charging–discharging of it.

Keywords: Battery, charging-discharging, Energy harvesting, Lifetime, Wireless sensor network, Super-capacitor, Solar panels.

1 Introduction

The wireless sensor network is a network of nodes which work in cooperation to acquire data and send it to the gateway or the sink node. Sensor networks are formed from a collection of sensing nodes which communicate with one another, typically through wireless channels, in order to collect spatially distributed data about their environment. Such networks have the potential to provide better quality data than single or small numbers of individual sensors in applications such as natural and built environmental monitoring, process monitoring, security and surveillance. Wireless sensor networks (wsn) may be considered as the third wave of a revolution in wireless technology. They promise to have a significant beneficial impact on many aspects of our human existence. These benefits include more efficient utilization of resources, better understanding of the behavior of humans, natural and engineering systems, and increased safety and security. In order to be cost effective in many applications, the sensor nodes must be low cost and low maintenance. This presents challenges in terms of sensor calibration, packaging for survival in harsh environments and, particularly, the efficient supply and utilization of power.

The basis of the wsn is the nodes or motes. A mote/node is a unit component of the wsn. Typical mote consists of a sensor, processor and radio interface.

The basic components of a mote/node are:

1. Sensor
2. Power supply
3. Processor and memory
4. Radio interface.

• *Vaibhav .C. Lokhande is currently pusuing masters degree from Shivaji University , Kolhapur, Maharashtra.PH:9922231348. email:vaibhav.c.lokhande@gmail.com*

The basic functional diagram of a mote is shown below.

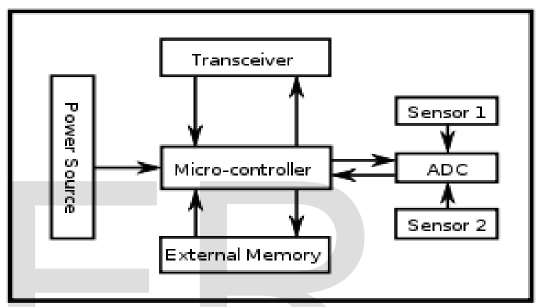

Fig 1 Functional Diagram of wireless sensor node (mote).

The functional diagram in figure 1.1 shows the basic blocks. The node has a power source, microcontroller, transceiver, sensor and external memory. However, the memory block is optional and is used as per the application's requirement. The main function of the node is sensing and sending the data to the base station. The sensor is a device which senses a physical parameter and generates or gives out an electrical signal/output. There can be many sensors on the node depending on the physical parameters being monitored. The function of the microcontroller is to control the functioning of the node. It can run the operating system like TinyOS, and control the functioning of the node. Also, in addition to that the micro controller plays an integral part in the working of the network. The micro controller is the main decision making and processing unit on the node. It controls the wakeup and sleep cycle of the node and manages the power of the node. The data from the sensor is processed by the controller and sent to the transceiver. The micro controller also logs the data onto the external memory. The transceiver block provides the communication capabilities to the node. It is the wireless interface using which the node communicates. There are many wireless interfaces available which can be used for communication between the nodes. The transceiver transmits

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as well as receives the data from other nodes. The data is forwarded to base station with the help of other nodes.
The basic functional diagram of a wsn is shown below.

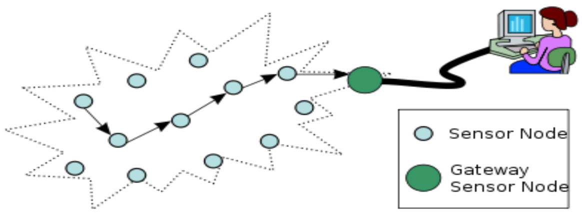

Fig 2 Functional diagram of Wireless Sensor Network.

The wireless sensor network in figure 1.2 is a network of sensor nodes which cooperatively work to transmit data through the network. The nodes transmit data through the network based on the routing protocol used. This protocol determines the path and the way in which communication will take place. The nodes relay the data to the sink node. The sink node aggregates the data from the nodes and then transmits it to the base station. The base station logs the data onto the memory and makes it available to the end users. The base station acts as a gateway- giving an interface between wireless sensor network and other networks. In some cases the sink node and base station may the same and in some large networks there may be multiple sink nodes. The network has substantial influence over the node's energy.

2. Applications of WSN:

The concept of wsn has gained interest due to various sensors it can support. The sensors and sense many physical parameters such as temperature, humidity, seismic vibrations, speed, light, sound etc. The sensors available can be utilized in different applications and ambient conditions. This spectrum of applications includes security, monitoring of space assets for potential and human-made threats in space, ground based monitoring of both land and water, intelligence gathering for defense, environmental monitoring, urban warfare, weather and climate analysis and prediction, battlefield monitoring and surveillance, exploration of the Solar System and beyond, monitoring of seismic acceleration, strain, temperature, wind speed and GPS data.

Military Application:

The main advantage of the wsn is the ability to perform in remote and hostile conditions. The motes can be deployed in region of interest and utilized to reliably monitor the area. Most the military application of wsn is event driven. Motes will communicate data when the event crosses the threshold. These thresholds include sensing of seismic vibrations caused by movement of heavy transportation carriers, sudden change in ambient noise and temperature, detection of human presence (Sniper detection) etc. Some of the military applications of sensor networks are monitoring friendly forces, equipment, and ammunition, battlefield surveillance, battle damage assessment, and nuclear, biological, and chemical attack detection. WSN promises a highly coordinated smart self organizing network which provides vital and reliable data. Such ' intel ' provides a decisive advantage in battlefield.

Environmental monitoring:

In the present day scenario where the global community is facing life threatening problems such as Climate change, biodiversity loss, pollution etc, the wsn can help us in monitoring various environmental parameters as well as animals, birds and crops. Such monitoring may also help us in pinpointing the exact causes and help in mitigating the adverse effects of environmental phenomenon by timely preparedness. The network of motes deployed in an environment can monitor an array of parameters. It can also be used in disaster management by alerting the people and authorities of natural disasters. A similar monitoring for two volcanoes in Chile successfully proved that wsn can perform reliably in harshest conditions to provide with information which can help in disaster management Crops and farming are the most vulnerable to climate change. The wsn can provide a constant monitoring platform wherein most of the parameters required for plant growth can be monitored.

Health care Application:

The developments in implanted biomedical devices and smart integrated sensors make the usage of sensor networks for biomedical applications possible. Some of the health applications for sensor networks are the provision of interfaces for the disabled, integrated patient monitoring, diagnostics, drug administration in hospital, tele-monitoring of human physiological data, and tracking and monitoring doctors and patients inside a hospital.

While studying the wsn it is necessary to understand the detail working of the node and its components. The applications for which, it is being utilized. The application may require constant monitoring and data transmission or it may be event driven. Depending upon the application optimized choices is to be made regarding the components of the node and other factors such as routing protocol. It is apparent that the most important problem for a wsn is the power. Power on the mote is limited. Mostly the motes are being battery powered and can last upto 2-3 years. However, with use of passive techniques to save power, can extend the lifetime by some margin if not much. These techniques include task scheduling, routing protocol etc. The energy usage is optimized and all the functions of the mote are scheduled so as to conserve the energy available. These methods are only a way to optimize and conserve energy. With a limited power source such as battery which has its own internal losses, such techniques do not contribute much. The answer lies in the energy harvesting from the environment to keep the power source replenished. This not only ensures uninterrupted supply but also a reliable network.

3. Literature Survey:

There has been considerable effort in building of wireless sensor node. Most of the earlier node we powered by battery solely. However, attempts were made to make nodes which were capable of harvesting energy from the environment. Some of them tried to make node powered by rechargeable battery or by super-capacitors.

Heliomote[1]: This mote tried to make a node, which was powered by two AA NiMH batteries. To charge the batteries the solar panel output was directly connected to batteries through a diode. It does not perform MPPT (maximum power point tracking) hence the batteries can only be charged when the solar panel output is 0.7 V higher than the battery voltage. The 0.7V drop is introduced by the diode connected to solar panels to stop the reverse flow from the battery.

Everlast: F Simjee and P. Chou [2] built a node which completely cut out the battery factor coming in to play. The node is powered by a super-capacitor which has high capacity. The super-capacitor is connected to the solar panels through MPPT circuitry. Since the node is powered by only a super-capacitor, any available solar panel output should be used efficiently. This is one of the reasons to introduce MPPT in the node. The node uses V_{oc} lookup table type MPPT. It requires a dedicated microcontroller and hardware to perform MPPT.

PUMA[3]: PUMA is designed to maximize the utility of ambient power from a sensor system with multiple ambient power sources, leading to lower power draw from the battery. The PUMA technique uses a power routing switch to route multiple power sources to multiple subsystems. The higher utility of ambient power is achieved through a combination of MPPT and power defragmentation. However, it requires MCU control based on input from light or wind sensors.

Prometheus[4]: Xiaofan Jiang, Joseph Polastre, and David Culler in their paper "Perpetual Environmentally Powered Sensor Networks" introduced a node capable of harvesting energy and storing it in super-capacitors. The solar panel output is directly connected to the super-capacitors. These capacitors when fully charged will charge the battery. And with sufficient voltage on the solar panels the super-capacitor will power the node. The node normally works on the super-capacitor's energy seldom drawing current from the battery. Since the battery is used less, it needs to be charged less number of time. This increases the overall life of the node.

In this paper, such a node will be attempted, which will harvest energy and charge the super-capacitor and battery separately. Solar panels will be used to harvest energy and then charge the energy storage elements. To maximize the life of the node, solar panels will power the node when both the other sources are charged and there is sufficient output available from the panels. This will reduce the stress on the battery and the super-capacitors.

4. Energy harvesting:

Energy harvesting is a technique that captures, harvest or scavenge unused ambient energy (such as vibrational, thermal, wind, solar, etc.) and convert the harvested energy into usable electrical energy which is stored and used for performing sensing or actuation. The harvested energy is generally very small. Energy harvested from the ambient are used to power small autonomous sensors that are deployed in remote locations for sensing or even to endure long-term exposure to hostile environments. The operations of these small autonomous sensors are often restricted by the reliance on battery energy. Hence the driving force behind the search for energy harvesting technique is the desire to power wireless sensor networks and mobile devices for extended operation with the supplement of the energy storage elements if not completely eliminating the storage elements such as batteries.

The most widely used energy harvesting devices rely on solar, thermal, RF, and piezoelectric sources of energy.

Photovoltaic (PV) or solar cells convert light energy into electricity. Photovoltaic cells have the highest power density and highest power output of the various energy harvesting devices.

Thermoelectric energy harvesters convert heat into electricity. They consist of arrays of thermo-couplers that generate voltage in response to a temperature differential across their bimetal junctions (the Seebeck effect). The reverse is also true: impressing voltage on a thermocouple junction heats one junction while cooling the other which is the basis for heat pumps (the Peltier effect).

RF energy harvesters capture ambient RF radiation, rectify it, boost it, and use it to power ultra-low-power embedded devices. RFID works on that principle, though by reacting to a strong RF field that is directed at the sensor and not by harvesting ambient RF.

Piezoelectric transducers convert pressure or stress into electricity. The vibration from motors, airfoils, or roadbeds commonly power piezoelectric energy harvesters that, in turn, power a processor.

Energy Source	**Performance (Power Density)**
Solar (direct sunlight)	100 mW/cm3
Vibrational Micro-Generators	4 µW/cm3
Piezoelectric Push Buttons	50 µJ/N
RF and Inductive	Wide range
Thermal	0.5-10mW (20 degree gradient.)

Table-1. Comparison between power densities of various energy sources

The table 1 compares different energy sources used for harvesting energy. Out of all the sources, solar energy produces highest output. The RF and thermal sources also produce considerable output but are still too low to be harvested for wireless sensor network.

5. Super-capacitors:

Conventional capacitors consist of two conducting electrodes separated by an insulating dielectric material. When a voltage is applied to a capacitor, opposite charges accumulate on the surfaces of each electrode. The charges are kept separate by the dielectric, thus producing an electric field that allows the capacitor to store energy.

Capacitance C is defined as the ratio of stored (positive) charge Q to the applied voltage V:

$$C = Q/V \quad \ldots (1)$$

For a conventional capacitor, C is directly proportional to the surface area A of each electrode and inversely proportional to the distance D between the electrodes:

$$C = E_o E_r A/D \quad \ldots (2)$$

The product of the first two factors on the right hand side of the last equation is a constant of proportionality wherein E_o is the dielectric constant (or "permittivity") of free space and E_r is the dielectric constant of the insulating material between the electrodes. The two primary attributes of a capacitor are its energy density and power density. For either measure, the density can be calculated as a quantity per

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unit mass or per unit volume. The energy E stored in a capacitor is directly proportional to its capacitance:

$E = ½ \times CV^2$ ... (3)

The power P is the energy expended per unit time.

The internal components of the capacitor (e.g., current collectors, electrodes, and dielectric material) also contribute to the resistance, which is measured in aggregate by a quantity known as the equivalent series resistance (ESR). The voltage during discharge shown in figure 2.2, is determined by these resistances. When measured at matched impedance (R = ESR), the maximum power P_{max} for a capacitor is given by:

$P_{max} = (V^2)/ 4*ESR$ ... (4)

This relationship shows how the ESR can limit the maximum power of a capacitor. Conventional capacitors have relatively high power densities, but relatively low energy densities when compared to electrochemical batteries and to fuel cells. That is, a battery can store more total energy than a capacitor, but it cannot deliver it very quickly, which means its power density is low. Capacitors, on the other hand, store relatively less energy per unit mass or volume, but what electrical energy they do store can be discharged rapidly to produce a lot of power, so their power density is usually high. Super-capacitors are governed by the same basic principles as conventional capacitors. However, they incorporate electrodes with much higher surface areas A and much thinner dielectrics that decrease the distance D between the electrodes. The super-capacitor has a large number of cycles, often in numbers of more than hundreds of thousands. This usually makes the lifespan longer than the calendar life for the battery. There are, however, a number of parameters that has an impact on the lifetime of a super-capacitor. If the capacitor is subjected of too high voltage or high temperature the life length is drastically shortened. The lifetime is halved for each 100mV or 10^0C above the rated voltage or temperature. Therefore it is important to keep both the voltage and the current at reasonable levels, as high currents leads to I^2R losses which gives higher temperatures. The ageing process in a super-capacitor is due to the increased reactivity of the electrolyte, which increases with impurities from reduction or oxidation. This leads to an increasing internal resistance, lower capacitance and increased self discharge rate. The reduction process is accelerated by higher voltages; therefore it is important to monitor the cell voltage.

Standard Charging Discharging Characteristics:

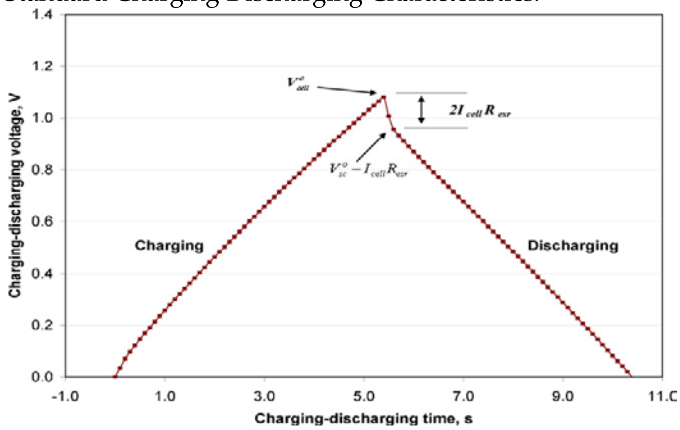

Fig 3 Charging Discharging characteristics of a super-capacitor.

6. Hardware Implementation:
Block Diagram:

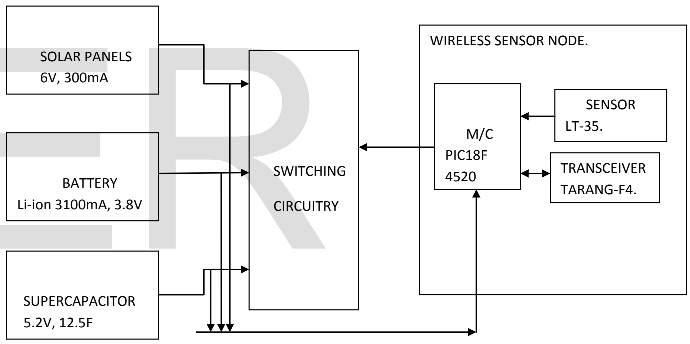

Fig 4 Block Diagram of the energy harvesting node.

The block diagram of the node is shown in figure 3.1. The node has three sources, namely solar, super-capacitor and battery. The node itself has a microcontroller, sensor and transceiver. The microcontroller will not only collect the data from the sensor but also keep monitoring the output of the sources. Depending on that it will switch between the sources. The microcontroller will have the responsibility to decide on which source to switch depending on the conditions. The solar panels can also be used to power the node directly. This attempt has not been done in previous wireless sensor platforms having super-capacitors and battery. For this very reason we need switches.

Sensor:

The sensor being used is a temperature sensor LM35. This is a linear semiconductor type sensor. The sensor produces output in milli-volts. The output is proportional to the temperature. There is a change of 10mV/°C.

The LM35 does not require any external calibration or trimming to provide typical accuracies of ±¼°C at room temperature and ±¾°C over a full −55°C to +150°C temperature range .The device is used with single power supply, or with plus and minus supplies. As the LM35 draws only 60 μA current from the supply, it has very low self-heating of less than 0.1°C in still air.

Solar panels:

The solar panel shown in figure 2 which is being used has an output of 6 V (open circuit voltage V_{oc}.) and 300 mA (short circuit current I_{sc}). Its dimensions are 120mm X 130mm. Its small size and better output reduces the need for MPPT, maximum power point tracking.

Fig 5 Solar panels producing 6V-300mA.

Super-capacitor:

The super-capacitor used is a LSUC 25F, 2.6V capacitor. The reasons for selecting capacitor with such capacity are:

1) Charging current available.
2) Charging time required.
3) Useable energy available for the capacitor.

Maximum charging current available from the solar panels is 300mA. However, it is not possible to get the continuous output of 300mA always. The super-capacitors are charged by current varying from 0-300mA. This increases the charging time.

Charging time is one of the factors which we have to consider for the application of wireless sensor node. Since, solar energy harvesting is done we have limited time window during which the super-capacitor needs to be charged. The charging time depends upon the time constant and the maximum current available from the power source.

The capacitors with different capacity where theoretically eliminated because of the above factors and the super-capacitors with 25F capacitance were found to be suitable. After taking the I-V and C-V characteristics with the help of battery cycler shown in figure 3.3 and 3.4, it was found that the 25F capacitor has a charging time of about 600-700 seconds when the charging current is 100 mA. This proves to be optimum as per the requirement of the node.

Table 2 Comparison between capacitors of different capacity.

Parameters	5F Capacitance.	25F Capacitance.	50F Capacitance.
Charging Time. (s) (Current 100mA using Battery cycler)	410	767	1603
Charging time (s) (When connected to the Solar Panels Directly with minimum 100mA current)	550-600	900-1000	1800-2000
Useable Energy (J)	32.8	164	328

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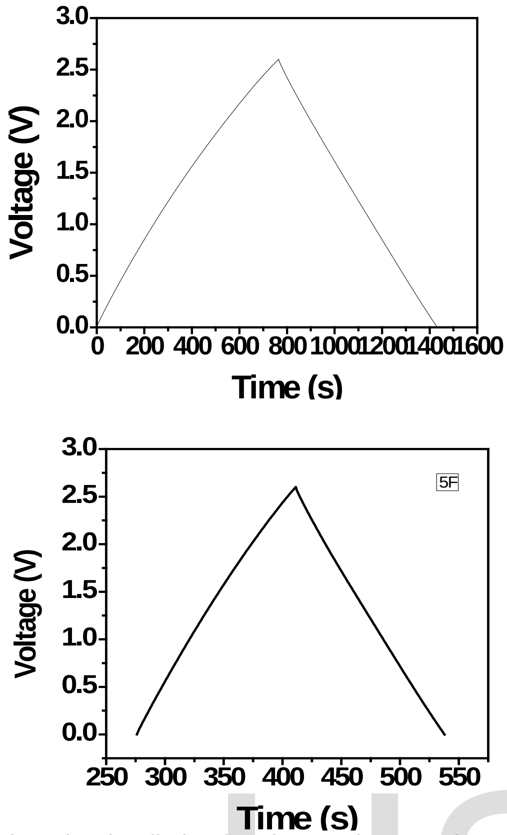

Fig 6 Charging-discharging of 25F and 5F capacitors

The battery used is Li-ion Battery shown in figure 3.5. The battery provides 3100mAh i.e 11.78Wh at 3.8V. The energy of the battery is 11.78 X 3600 = 42408 J. Batteries are often the limiting factor of a node's lifetime. Therefore, lithium ion battery was chosen because it has a large number of recharge cycles, high charge density, low leakage, lack of memory effect, and provides sufficient voltage with one battery.

Other specifications:

Input voltage =4.35V.

Output voltage =3.8V

Output current =520mA

Dimension (WXHXD) = 53.5 x 80.0 x 5.4mm

Microcontroller:

PIC18F4520 has been selected as the onboard microcontroller. The PIC has many important tasks such as monitoring, collecting data, controlling and decision making. It has to monitor the voltages from the three sources and then decide on which one it needs to switch to. The PIC also has to collect the data from the sensor and then transmit it through the transceiver. The role of PIC is very important as it controls the switches as well as performs the duty of traditional wireless sensor node. The PIC18F4520 is a 40 pin IC which has the operation voltage range from 2 - 5.5 V. It works on nano-watt technology which is ideal for our application.

Wireless Transceiver:

The wireless transceiver used is Tarang F4 shown in figure 3.6. It works on same protocol as Zigbee, i.e. IEEE 802.15.4. The operating frequency is 2.4 GHz (ISM Band). The Tarang F4 needs 3.3V-3.6V supply voltage and draws current of 45mA when transmitting and 50mA when receiving.

7. Working and Circuit Diagram:

Circuit diagram:

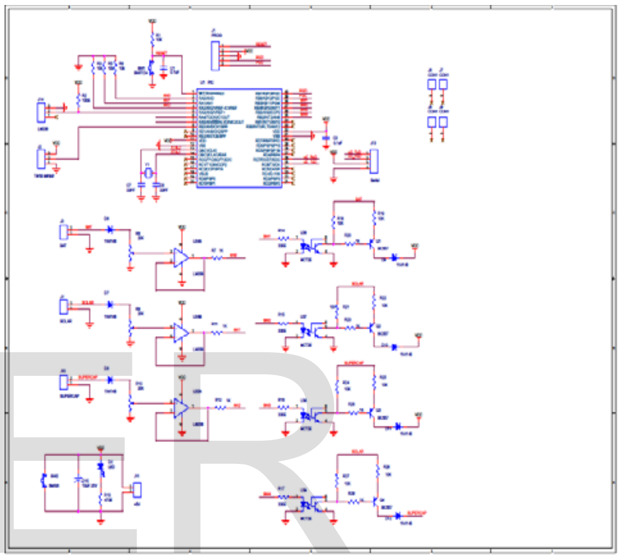
Fig 7 Circuit diagram of the wireless sensor node constructed having energy harvesting and switching capability.

The node now has three power sources which can power up the node. The role of microcontroller is to monitor the output voltage of the sources and then switch to the appropriate source. The main aim is to use the battery as less as possible. The super-capacitor can fill in whenever it is charged. Whenever both the sources, battery and super-capacitor, are charged the solar panel can power up the circuit.

The threshold voltages have been decided so as to facilitate the microcontroller to switch between the sources. The V_{cap} is the voltage across the capacitors. Two capacitors of 25F have been connected in series to raise the voltage across them to 5.2V. The V_{sol} is the solar panel output voltage. And V_{batt} is the battery voltage. The circuit requires a minimum of 3.3V for its reliable operation.

When the node starts its operation it will do it on the battery. It will first read the data from the sensor and then it will take voltage readings

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from the sources. If the V_{cap} and V_{sol} are both at their maximum voltages then the microcontroller will switch onto the solar panels and disconnect the battery. However, if there is no solar panel output and V_{cap} is above 3.3V it will switch to super-capacitors. Whenever the voltage V_{cap} falls below this threshold, the processor will switch to battery. The node will continue its operation on battery until there is sufficient voltage (>3.7V) from the solar panels. The solar panels under full sunlight condition produce 6V and 300mA. It can charge the super-capacitors and power the node simultaneously. Once the super-capacitor is fully charged the processor will wait until the solar panel output falls below the threshold and then switch in the super-capacitors. When the battery voltage falls below 3.7V, the solar panels will charge the battery but it will do it after fully charging the super-capacitor. Since the super-capacitors require less time for charging and there is no guarantee of constant solar radiation, care has to be taken to keep the node alive. Battery on other hand requires more time to charge, typically 3-4 hours through solar panels. Until then the super-capacitor can act as a backup.

The switching is done by processor through opto-couplers MCT2E. The reason for using opto-couplers was to establish isolation so as to maintain the reliable switching. Traditional transistorized switches could not provide the reliability because of the accidental switching off due to back voltages. With the use of opto-couplers this problem was addressed.

8. Result and Conclusion:

The circuit was successfully tested in various situations. These situations were manipulated to check whether the switching takes place smoothly or not. The priority was given to save the battery and charge the super-capacitor as much as possible. The super-capacitor will fill in the periods when no sunlight is available. If the period is too long the super-capacitor will eventually drain out and circuit will switch to battery.

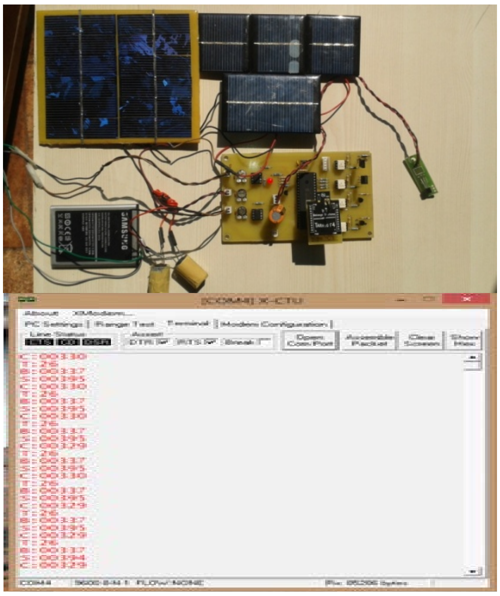

Fig: 8 Circuit connected to three sources and the Data transmitted via RF Interface.

The circuit shown in figure 8 was connected to all the power sources and kept under sunlight. The circuit worked properly.

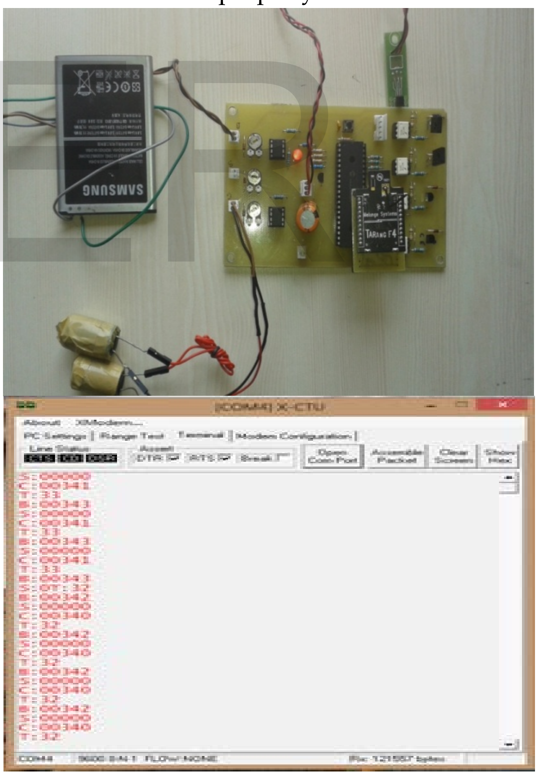

Fig: 9 Circuit connected to battery and super-capacitor and the Data transmitted via RF Interface.

The solar panels are disconnected and the circuit is powered by super-capacitor and battery. The circuit will work on super-capacitor tank if the voltage is above the threshold. The super-capacitor tank will power the node until the voltage falls below 3.3 V. After that the circuit will automatically switch to battery.

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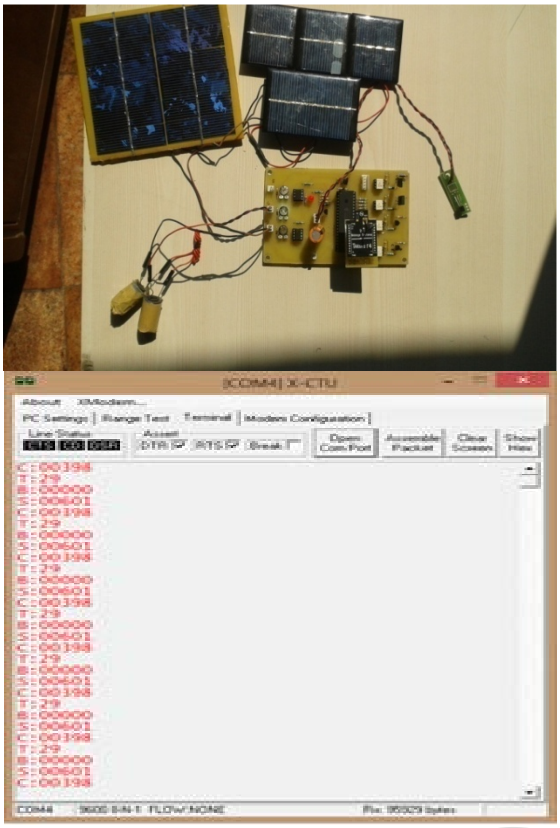

Fig: 10 Circuit connected to solar and super-capacitor and the Data transmitted via RF Interface.

The circuit shown above in figure 10 is powered by solar panel and super-capacitor. The circuit works on the solar panel if the output is higher than 3.7 V. If not, the circuit switches to super-capacitor. When the solar output is sufficiently high it will power the circuit and charge the super-capacitor as well.

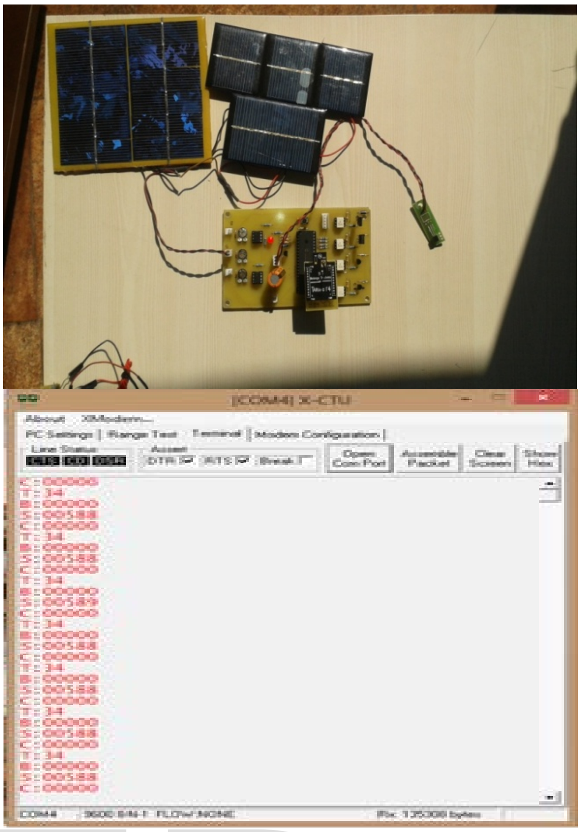

Fig: 11 Circuit connected only to solar and the Data transmitted via RF Interface.

The circuit shown above, fig 11 is powered by solar panels. The circuit will work until the solar output is available.

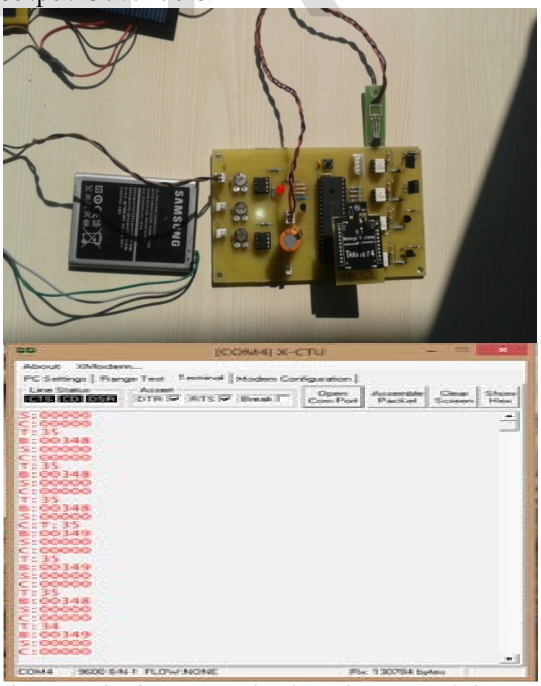

Fig : 12 Circuit connected only to battery and the Data transmitted via RF Interface.

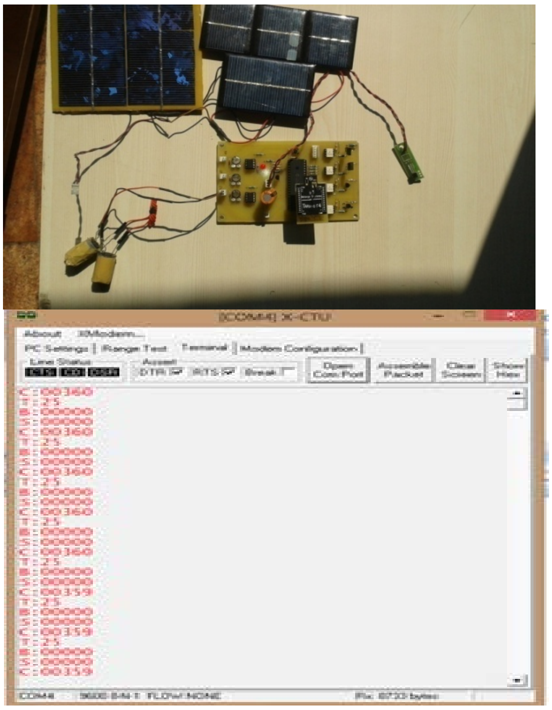

Fig: 13 Circuit working only on super-capacitor and the Data transmitted via RF Interface.

The figure 13 shows circuit working only on the super-capacitor tank. The circuit transmitting after every 15 minutes theoretically can work for 5 days and 19 hours. But the ESR and internal leakages reduce this time. With the super-capacitor at 100% efficiency, circuit works for 2-3 days but as the efficiency reduces (20%) the super-capacitor tank can power the circuit for 1-2 hours only.

Fig: 14 Circuit charging onboard Super-capacitors through solar panels.

The figure 14 demonstrates charging of super-capacitor through solar panels. The output of the solar panels is 6.01 V and the super-capacitor voltage has risen from 3.95 V to 4.41 V.
Similarly the battery is charged by the solar panels when the battery voltage falls below threshold of 3.7 V. When both sources are drained the solar panel will first charge the super-capacitor tank and the charge the battery. Since super-capacitor requires less time to charge

than battery it is charged first. Once charged the super-capacitor can work for at least 2 hours, by which time battery is substantially charged. The node transmits temperature, and voltage output of the power sources to the base station. The data is received and serially transferred to the computer.

6 Energy Calculations:

The classical energy consumption model only considered the energy consumption of the transceiver. It did not consider the energy consumed by the CPU, sensor and other components on the node which significantly amount for the energy consumption. This consumption is significant in wsn where energy is much priced. Thus it will be of tremendous significance if we are able to calculate all the energy consumption.

Sensor's Energy Consumption:

Sensor connects the node to the physical world. The role of the sensor is to sense the physical parameter and generate electrical signal. This electrical signal is what constitutes the heart of the communication. Sources of sensor power consumption are: signal sampling and conversion of physical signals to electrical signals, signal conditioning and analog to digital conversion (ADC).

Let the I_{sens} be the current required for the sensing activity and T_{sens} be the time required for sensing activity. The energy required for the sensing activity is

$$E_{sens} = V_{sup} * T_{sens} * I_{sens} \qquad \text{...(6)}$$

Where, V_{sup} = supply voltage.

Microprocessor Energy consumption:

The energy for processing and aggregation of the data mainly consumed by the micro-controller also includes the energy spent for performing the task such as data collection from the sensor and voltage sources. This also accounts for the energy dissipated by the leakage current.

$$E_{proc} = \text{Total Energy} = E_{active} + E_{standby} \qquad \text{... (7)}$$

$$\text{Time} \times I \times V = T_{active} \times I_{active} \times V + T_{standby} \times I_{standby} \times V$$

Transceiver Energy Consumption:

The energy consumed by the transceiver either while transmitting or receiving the data. This also includes the energy required by the amplifier to power the antenna for long distance transmission.

$$E_{trans} = E_{t/r} + E_{amp} \qquad \text{... (8)}$$

Where, E_{trans} = Total energy consumed by the transceiver.

$E_{t/r}$ = Energy consumed during the transmission and reception.

E_{amp} = energy consumed by the amplifier.

The energy consumed by the designed node according to the empirical model is:

E_{sens} = 0.2mJ

E_{proc} = 148.5mJ

E_{trans}= 165mJ

Theoretically, the energy consumption of the node is 313.7mJ. But the using DC ammeter the current consumed by the node is 110mA.

E_{tot}= 363mJ.

The energy sources and storage devices on the node will give an idea about the total energy available and energy consumed by the node. This will help us in estimating the life time of the wsn.

Energy Sources:

The battery is the primary source on the node. The energy available can be calculated as

E_{bat} = Wh *3600

E_{bat} = Ah * Vbat * 3600

E_{bat} = 3.1 * 3.8 * 3600 = 41040 J

Thus, the energy available with the battery is 41040 Joules.

Total time of operation = 41040/ (0.363*4*24*365) = 3.22 years.

If the circuit were to operate only on the battery it would continue to function for little more than 3 years.

Solar Panels:

The output from the solar panel is instantaneous and dependent on the solar radiation available. Therefore, the power rating of the solar panels is the maximum output that can be received from the panels at any given time.

$$P_{sol} = V_{oc} * I_{sc} \qquad \text{... (9)}$$

Where, V_{oc} = Open circuit voltage.

I_{sc} = Short circuit current.

P_{sol} = 1.8 W.

Thus, the output from the solar panel varies from 0-1.8 W. This output from the solar panels can be used to charge the super-capacitor and the battery as well as power up the node. Solar panels replenish the power sources on the node and the shallow charging of the battery also benefits the battery's life.

Super-capacitor:

The super-capacitor has high power density but lower energy density. This gives them the ability to charge and discharge quickly. However, the energy stored is lesser than the battery.

The energy available with the super-capacitor can be determined by:

$$E = \frac{1}{2} CV^2$$

Two super-capacitors, each of 25F capacity and 2.6V rating are connected in series. Thus their capacitance halves and the voltage across them becomes twice.

$$E = 338 \text{ J}$$

However, for our application the super-capacitors become useless when the voltage falls below 3.3V. Thus the useable energy available with the super-capacitor is:

$E = \frac{1}{2} C (5.2^2 - 3.3^2) = 201.875$ J.

So the node has this much energy which it can be used for its reliable operation. Considering the energy consumption of the node for transmitting once (i.e. the node is on for 1 second) the super-capacitor will be able to sustain the operation of the node for 556 seconds of continuous transmission. If the node transmits four times in an hour i.e. after every 15 minutes, the super-capacitor will power the node for 139 hours. However, the super-capacitor loses 1-2% charge per day due to internal resistances. This shows us that the super-capacitor can successfully power the node throughout the night. And then can be recharged by the solar panels. This routine itself can sustain the node until the end of lifetime of the super-capacitors provided that solar irradiance is not absent for more than 30 hours.

Considering the above calculations, it can be concluded that, the energy harvesting and super-capacitor not only have increased the life of the node but also helped in reducing stress on the battery and improve its health so that it can be used for longer period of time.

The wireless sensor network having energy harvesting capabilities, has been tested and the result show that the life of the node has substantially increased. The energy calculation show increased lifetime.

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