SOLAR CELL SIZE REQUIREMENT FOR POWERING OF WIRELESS SENSOR NETWORK USED IN NORTHERN EUROPE

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Abstract: This paper investigate the possibilities of using solar cell panels for powering Wireless Sensor Networks (WSN) in Northern Europe. By using a power model of a WSN node and the PVGIS database we have calculated the required size of a solar cell panel for a node. With an active period of 48ms per minute, the size of the solar cell panel to supply sufficient energy must be larger than 1.1cm^2 in Rome, 1.5cm^2 in Berlin and 1.4cm^2 in Oslo in July. In December the size requirements have increased to 5.1cm^2 in Rome, 17.4cm^2 in Berlin and 58cm^2 in Oslo. Further north the size becomes too large to be feasibly to use.

Keywords: Wireless Sensor Networks, Solar Cell, Energy Harvesting

INTRODUCTION

Wireless Sensor Networks (WSNs) are composed of a large number of small nodes equipped with sensing devices, computing power and radio communication capabilities [1]. Our use of wireless sensor networks is for achieving situation awareness in an area monitoring systems. In order to achieve satisfactorily situation awareness, a large number of sensor nodes need to be used. The high number of nodes excludes any kind of maintenance, such as battery replacement, after the system has been deployed. Hence, the lifetime of the system is a compromise between the energy that the nodes carries when deployed (battery powered) and the measurement rate. The radio power consumption is determined by the data rate and the radio range [2]. This makes the networking function, the radio links and not the measurement function, by far the largest power consumer in a wireless sensor network.

Utilizing sleep mode has been suggested to extend the lifetime of a battery powered WSN [3][4]. A high sleep – active ratio will prolong the lifetime of the network. Extended lifetime may then be achieved at the expense of reduced measurement rate.

Another method for achieving extended lifetime for a WSN is to exploit the possibility of energy harvesting from the environment [5] [6] [7], where energy harvesting from the sun is giving the best performance.

In the presented work we are investigating the possibilities for harvesting power from a credit card sized (85.4 x 53.98 mm^2) Si solar cell panel at various locations in Europe. For our calculations we have used an example node similar to the TelosB from Crossbow.

POWER MODEL OF A WSN NODE

A block diagram of a typical WSN node is shown in Fig. 1. It consists of a microcontroller (MCU), a radio, a sensor block and a power module. When powered with a solar cell, a local charge storage or a battery is needed to store surplus energy for periods when sun irradiation is low or absent e.g. during the night, on overcast or rainy days.

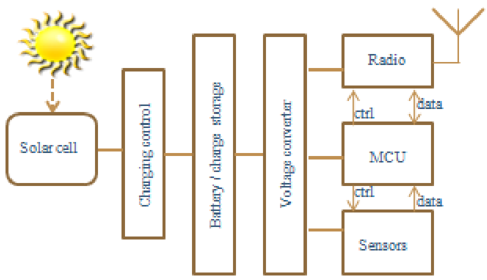

Fig. 1: Block diagram of a typical WSN node.

The power consumption of the main devices in different modes is summarized in Table 1. In this example we have used the MSP430 MCU and the CC2420 radio from Texas Instruments. The MCU has several sleep modes, but we assume that the real time clock (RTC) must be running in sleep mode in order to make the node wake up itself at given points in time. For such short range radios as the CC2420, the maximum power consumption is in the receive mode. The transmit power is programmable and the power output can be lowered for short ranges as shown in the table. For a network to operate where each node can hear many neighboring nodes, the radio will be in listen or receive mode most of the time.

Table 1: Power consumption of MCU and Radio in different modes (@3V).

Unit	Mode	Power
MCU	Active	1.5mW
	Sleep mode	6µW
Radio	Tx (0dBm)	52mW
	Tx (-10dBm)	33mW
	Tx (-25dBm)	25mW
	Rx	59mW
	Idle	1.3mW
	Power down	60µW
	Off	3µW

We define three states for the node: active, running and sleeping. Active state (P_A~60mW) is when the node can participate in networking. Running (P_M~2mW) is when the radio is down, but the MCU can do measurements. And sleep (P_S~10μW) is when only the RTC in the MCU is running.

Many WSN implementations are based on IEEE 802.15.4 and ZigBee. In this work we assume that a superframe structure is used, and that all local communication is performed within one frame. One superframe consists of 16 slots (N_F), and the length of one slot (T_S) is determined by the number of bytes for address and data. This is shown in Fig. 2 with one active and one sleep period. The active period consists of a superframe with beacons (B), receive (R) and transmit (T) slots.

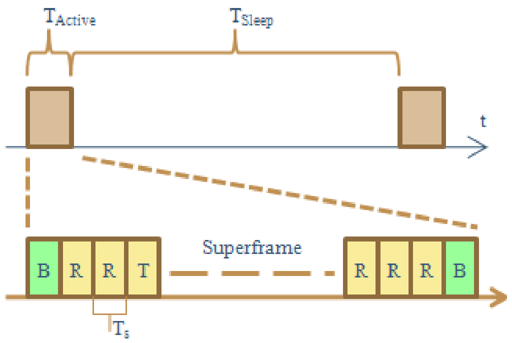

Fig. 2: Active sleep period with a superframe containing beacons (B), receive periods (R) and one transmit period (T).

During a superframe period, the power is consumed by three different functions: the transmission of messages (T), the reception of messages (R) and the measurements and control (M) performed by the MCU. The energy for each function is given by the slot time, T_S, the number of slots, $N_{T,R,F}$ and the power, $P_{T,R,M}$.

$$E_A = T_S N_T P_T + T_S N_R P_R + T_S N_F P_M \qquad (1)$$

Receiving, when the radio is in listen mode, has the highest power consumption. By defining the power ratio, $C_T=P_T/P_R$, between transmit and receive, the power ratio, $C_M=P_M/P_R$, between measurement and receive, the energy is determined by the number of slots used for transmission, N_T.

$$E_A = T_S P_R [N_F\ (1 + C_M) + N_T\ (C_T - 1)] \qquad (2)$$

In our example with a message length of 100 bytes, T_S=3ms, C_T=0.88 (for P_T=0dBm), and C_M=0.034, the energy consumed during one superframe or active period of 48 ms is 55 mJ.

SUN RADIATION IN NORTHERN EUROPE

We have investigated the possibilities for harvesting solar energy at different latitudes in Europe. We have chosen six different locations: *Rome 41°53', Berlin 52°31', Copenhagen 55°40', Oslo 59°54', Trondheim 63°26' and Tromso 69°39'*. Fig. 3 shows the average solar radiation on a horizontal plane as a function of geographical places and seasonal variations. The data are collected using the PVGIS database [8]. The database takes into account climatologically factors as well as the topological terrain that may give shadowing of the sunlight. Such shadowing effect will normally be more pronounced at higher latitudes.

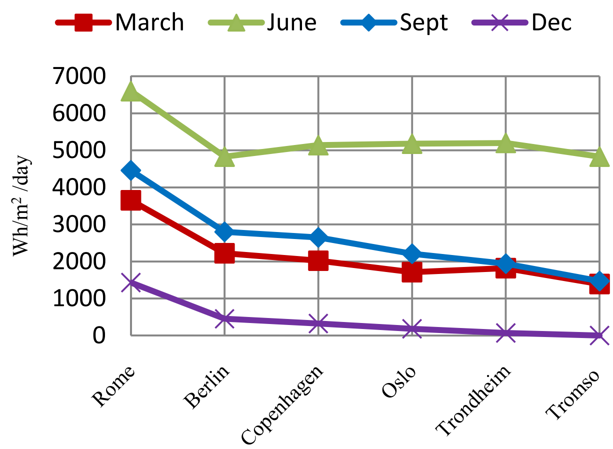

Fig.3: Average horizontal solar radiation as a function of geographical places and seasons.

Fig. 3 shows that there is very little difference in the solar radiation from Berlin to Tromso in the middle of the summer. At the spring and autumn equinoxes the radiation in Tromso is half as much as in Berlin. In December there is no solar energy available when the geographical location is north of the Arctic Circle.

Inclination of the irradiated plane plays a major effect. Having an optimal inclination angle of the plane gives more Wh/m^2/day, and the effect will be much more evident when moving towards north and between the autumnal and vernal equinoxes. However, deploying a WSN with solar cells should be as simple as possible. Thus, in our calculations, we have assumed that the cells are laying flat on the ground.

The efficiency of solar cells is dependent upon the technology [9]. For crystalline Si solar cells, the highest efficiency achieved is 25% [9]. However, in the following calculations, we will use typical credit card sized panel with 20% efficiency. Using this number, the peak power, P_{pk}, of such a panel can be estimated to 0.92W.

For calculating the output power from solar cells, the PVGIS database uses a default value of 14 % loss due to losses in cables, dirt on solar cell panels etc. In addition it also calculates losses due to temperature variations.

A shown in Fig. 1, there is a power unit in the WSN node consisting of a charge control unit for the battery, the battery itself and a voltage converter between the solar cells and the MCU/radio/sensor elements. The efficiency of these devices vary, but Taneja *et al.* [5] have measured the efficiency to be around 60% for the charge control unit, 66% for the battery and 50% for the voltage converter. This implies that less than 20 % of the energy harvested from the solar cell panel is usable for the electronic components in the WSN node (MCU, sensor elements and radio). In the following sections we assume that the losses/efficiencies are as described above.

Fig. 4 shows the average daily production of energy from a credit card sized solar cell panel at various locations at different seasons, taking into account the losses in the power unit. It is noticeable that in the summer season between equinoxes, the usable harvested energy is quite good at all locations. In Tromso in September month, the average daily energy production is ~715 J. However, in December, around winter solstice, the energy production is much lower for all locations. In Oslo, Trondheim and Tromso, the energy production is only 63 J, 16 J and 0 J respectively.

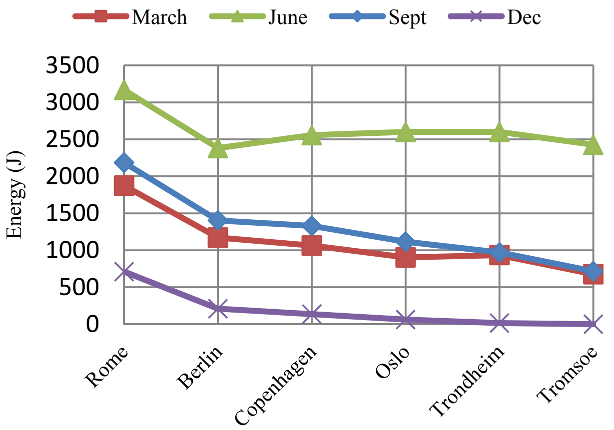

Fig. 4: Daily usable energy produced by a credit card sized silicon solar panel as function of locations and season.

At high latitudes the irradiance is very low during winter, which makes it extremely difficult to use solar powered systems. Above the Arctic Circle the sun is below the horizon for a period. There is a similar period during summer months where the sun shines 24 hours/day. This implies that solar harvesting systems are only possible to use at high latitudes during the summertime.

SLEEP - ACTIVE RATIO

As shown the energy consumed during one super-frame with one time slot of transmit of a data packet with 100 bytes, is 55mJ. Using the energy made available from the voltage converter – i.e. taking into account losses due to low device efficiencies– we can calculate how often we can run a superframe at the different locations in different seasons. The results are summarized in Table 2.

Table 2. Time (s) between frames at different locations and seasons.

Location	Month			
	March	June	Sept	Dec
Rome	2.5	1.5	2.2	6.7
Berlin	4.1	2.0	3.4	22.7
Copenhagen	4.5	1.9	3.6	34.8
Oslo	5.3	1.8	4.3	75.6
Trondheim	5.1	1.8	4.9	304.4
Tromso	7.0	2.0	6.6	∞

As seen from Table 2 it is not possible to transmit any data in Tromso in December.

If the time used for sending a superframe is 48 ms, we can use the figures in Table 2 to calculate the sleep/active ratio of the WSN system. It is only in Rome that the sleep/active ratio is larger than 300 in December allowing the network to be active once every 15 seconds. If we require a sleep – active ratio of 1250, i.e. one message every minute, it is possible to calculate the size requirements of the solar cell panel. The results are shown in Table 3.

Table 3. Solar cell size (cm^2) requirements with one active period per minute.

Location	Month			
	March	June	Sept	Dec
Rome	1.9	1.1	1.7	5.1
Berlin	3.1	1.5	2.6	17.4
Copenhagen	3.4	1.4	2.7	26.7
Oslo	4.0	1.4	3.3	58.0
Trondheim	3.9	1.4	3.8	233.4
Tromso	5.4	1.5	5.1	

If we limit the size of the solar cell to a credit card size, the solar energy available would be insufficient one month during winter in Oslo, two months in Trondheim and three months in Tromso.

POWER SYSTEMS / BATTERIES

Table 4 shows some typical parameters [10] for batteries or charge storage elements that could be relevant for use in a WSN. Alcaline and Li-Th-Cl [11] are not chargeable, which means that a WSN equipped with such batteries has a limited lifetime. Transmitting one superframe per second with N_T=1 and P_{Out}=0dBm, an alkaline battery would last 2 h/gram and a Li-Th-Cl battery would last 10 h/gram. For such a scheme to last for one month we would need an alkaline battery with a weight of 360 gram or a Li-Th-Cl battery with a weight of 72 gram. In most practical cases this is not acceptable.

Table 4. Parameters for energy storage elements.

Type	Ch	Wh/kg	kJ/kg	Wh/dm^3
Alcaline	N	110	400	320
Li-Th-Cl	N	700	2000	1100
NiMH	Y	95	340	300
Li-ion	Y	128	460	230
SuperC	Y	660		1390

When the node is powered with a solar cell panel, a chargeable battery or another charge storage element is needed to average the energy received during daytime over the whole 24h.

The charge storage capacity, i.e. the size of the battery, should be adapted to the 24h irradiance if we want to minimize it. The supercapacitor has the highest energy density but it would require more advanced charge controlling electronics than is required for battery charging [12].

DISCUSSION

The total size, weight and volume are major parameters for a wireless sensor node which might limit usability of the WSN. Electronic circuits have become very small and it is desirable to exploit this development to build very small sensor nodes. This is difficult to achieve if the power system constitute most of the node size. There are considerable challenges for improvements in the whole power chain if the objective for the node size is 1 cm^3.

When deploying a WSN using solar cells for energy harvesting, it is always a possibility that the placement of the solar panel is not optimal. This will of course lead to larger sleep/active ratios. The PVGIS database calculates average values, so on a rainy day, the amount of energy harvested can be substantially lower that the values shown in Fig. 4.

A lot of energy is lost in low efficiency in all stages from the solar cell panel ($E_{ff\text{-}scp}$), through the charging control ($E_{ff\text{-}cc}$), battery/charge storage ($E_{ff\text{-}bat}$) and voltage converter ($E_{ff\text{-}conv}$). The total efficiency is:

$$E_{ff-tot} = E_{ff-scp} * E_{ff-cc} * E_{ff-bat} * E_{ff-conv} \quad (3)$$

In our example with $E_{ff\text{-}scp}$=20%, $E_{ff\text{-}cc}$=60%, $E_{ff\text{-}bat}$=66% and $E_{ff\text{-}conv}$=50% efficiency the $E_{ff\text{-}tot}$ is as low as 4%, which means that 96% of the energy is lost due to low efficiency in the electronic devices in the power chain. To achieve a sleep/active ratio of 300 in Copenhagen in December the $E_{ff\text{-}tot}$ must be increased to 9.5%.

CONCLUSION

Using solar cell powering of WSN-nodes is challenging, even for outdoor use, if a high measurement rate is required.

With the use of a rather large – credit card size - solar cell panel, the sleep / active ratio is good, around 30-40, around summer solstice for all the investigated locations. It is acceptable, between 50-150, around the spring and autumn equinoxes. However, the sleep / active ratio becomes unacceptably large around winter solstice at high latitudes. North of 50° the ratio is nearly 500, north of 60° it is more than 1500 and north of the Arctic Circle there is no energy to harvest in December. Using a WSN at very high latitude during winter, the node must be powered with batteries with a capacity that will last for eight weeks.

From our calculations, the sleep / active ratio can be reduced by improving the efficiency in the electronics devices and by optimizing the listening / transmit ratio of the radio link. If a much smaller solar cell panel is required due to size constraints in the node, efficiency in the power chain must be considerably improved.

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