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Extended summary

ZIGBEE WIRELESS SENSOR NETWORK TECHNOLOGY TO MONITOR THE ELECTRIC ENERGY PRODUCED BY A MEAN-SIZE PHOTOVOLTAIC PLANTS

Curriculum: Ingegneria Elettronica, Informatica e delle Telecomunicazioni

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Abstract. In this document we show an application of the ZibBee protocol of wireless sensors networks (WSN), with the aim of monitoring the electric energy produced by a mean-size photovoltaic plants and other parameters useful for maintenance and fault-diagnostics. The control is done at a single photovoltaic module. In practice, the control circuit will be inserted in the same junction box of the photovoltaic module and the wireless network will be configured automatically.

The monitoring and control of the energy produced by a photovoltaic system is very important because the energy produced has a direct impact on cash flow which determines the economic convenience of the investment on the photovoltaic plant. Nowadays, the most diffused control systems of energy are that made at the level of the static DC / AC converter; these group one or more strings, so a usually high number of photovoltaic modules, it is possible in this way to see if the plant is producing energy efficiently, but does not identify the causes of inefficiencies due to the individual module. The causes of failure may be varied: dirt on the surface, shading, electrical breakdown, damage or even theft and, of course, the inefficiency may derive from more than one module. The data acquisition system proposed in this paper takes into account the single module

with sensors located within each junction box. The acquired data are evaluated by a software that identifies the causes of failure by distinguishing the abnormal situations from the normal ones: for example, a failure in producing energy can be either due to an electrical fault or to the absence of solar radiation during the night: a comparison between the single module and all the others identifies if the situation is normal or abnormal.

More specifically, the handling of each photovoltaic module allows you:
- to monitor other physical as well as voltage and current (for example temperature, motion, digital inputs) by increasing the production of energy;
- the module allows a more detailed planning of maintenance (cleaning modules, unshadowing, substitutions) and a review of the effectiveness with a consequent reduction in operating costs;
- the control in addition to the monitoring, that you can take automated actions to manage events and to increase the conversion efficiency of the module;

Keywords: data acquisition, monitoring, photovoltaic module, photovoltaic plant, zigbee wireless sensor network.

1 Tecnology

1.1 ZigBee

The technology utilized in this work refers to wireless sensor network with ZigBee protocol [3].

A *wireless sensor network* has two main functional aspects: measurement and communication. Each sensor device works as a communication node in the network topology. The network consists of sensor devices that communicate with other devices. As the devices communicate wirelessly, no network cabling is necessary. A device joins the network by being deployed in the wireless communication range of a neighbouring device. In a medium-sized photovoltaic system, with a few thousand modules, avoiding the cost of wiring is quite important.

The *ZigBee standard* (Table A) specifies the application layer of a wireless personal area network in a small area and a low communication rate.

A near-field small scale network is easily configured and up to sixty-five thousand devices can be managed. The network is typically configured in a star, mesh or cluster tree topology. Devices are classified into two types depending on the supported functions (Figure 6): Reduced Function Device (RFD) or ZigBee End Device (ZED) that simply transmits and receives data signals, and a Full Function Device (FFD) which in addition to transmit and receive data, interconnects the network nodes with router functionality. The radio sensitivity can be changed depending on the environment surrounding the devices. One of the routers assumes the role of network coordinator (COO) from the first moment of its formation.

The main difference between the two types is that an FFD, with the responsibility of the routing, must be continually active (awake), while an RFD can spend much of his time deactivated (asleep), becoming active only when it is necessary to send data, either by itself or being activated only by an external interrupt.

The end devices (RFD or ZED) can be further classified as Sleepy (SED) or Mobile (MED) to differentiate the situation in which they cannot be reached because they are inactive or because, being mobile, are currently out of radio range. The radio sensitivity can be changed depending on the environment surrounding the devices.

1.2 Power and Routing

The wireless sensor nodes are powered by Ni-Ca rechargeable batteries, which are recharged by the solar module itself; in order to increase the battery life, it is possible to decrease the dissipation of energy by putting the device in standby (sleepy) and turn it on again (wake-up) only when it is necessary to take measurements and transmit them. The routers, which must deal with the management of the network must always be active, and therefore they cannot lose power; this is why their energy loss is bigger.

In any case, to cover a photovoltaic (PV) field are theoretically necessary only few routers: as shown in Figure 1 an area of 5000sqm, with approximately 1000 modules with about 30m of operating range, is covered with 7 routers.

A device transmits data to the PC via a wireless communication link. The PC works as a base station that controls and manages the network. If a remote device is placed out of the radio-effective area of the PC, its data signal is

Interconnected by other devices and reaches the PC. The data from the remote wireless sensor nodes are collected by the local node, which is dedicated to this function and is called Data Sink (Figure 6).

1.3 Monitoring

The system we realized allows the monitoring to a greater level of detail (Figure 2), of all the parameters of a single module: in this way the system is effective because it allows to verify the energy production, to diagnose faults or malfunctions and theft, to record maintenance interventions or special events related to the single module; particularly, the remote diagnosis at this level of detail simplifies a lot the maintenance by reducing costs and response times. For each module it is possible to detect:

- The electrical voltage and current, and then from these the power and energy produced in kWh;
- The temperature and thus take the corrective action to decrease it;
- The acceleration in the three spatial directions and then see if it is the action of the wind or of a thief, and act accordingly to it. For example, for adjustable panels, it is possible to align them in the direction of the wind while, in the event of a theft, to send a message to the security service
- In addition, each module is encoded by both the MAC address of network node and a mnemonic code that is assigned during the configuration of the network (for example. "String number-unit number), allowing a visual control over the entire geometric arrangement of the PV field.

2 Hardware

2.1 Functional diagram of the circuit

The circuit designed is born as a proposal for manufacturers/assemblers of photovoltaic modules and it practically replaces the junction box which contains the by-pass diode; in Figure 3 it is depicted how the WL network node is connected to the PV module, included the bypass diode D10 and the low-value series resistor R33 for the current measurement.

The circuit, as well as providing a measure of the current and the voltage, and then of the energy produced in kWh, makes also available other parameters thanks to the inclusion of the following components: a temperature sensor to monitor the operating temperature of the module, an accelerometer to monitor the wind and the eventual theft of the module, two reed switches sensors activated by a magnetic field to be used as input for the geometric configuration of the network, i.e. to associate the physical network address (MAC address) to the geometrical position of the node in the net with a mnemonic code (eg num. of the string / num. of the module).

As depicted in the block diagram of Figure 4, it is provided the use of a PIC18F46K20 microcontroller to improve the programmability and the flexibility of the circuit, for example to overcome the maximum length of the input buffer of 128 bytes, and to have a greater control of the sensors of the node; however in our case the two analog inputs for voltage and current go directly to the analog inputs of the ETRX2 [1]. The module ETRX2 of Telegesis is a low-power and low-consumption 2.4GHz transceiver, based on the Ember EM250 [2] single chip with ZigBee/IEEE802.15.4 protocol. It is designed to be integrated into any device without the need to design the RF part.

Figure 5 shows the circuit in which additional and customizable (for future needs) features were provided; we list some components

1- Transceiver ETRX2 Telegesis
2- Antenna
3- Microcontroller PIC18F46K20
4- Bypass Diode
5- 0.12 Ohm 4W Resistor to measure current
6- Reed Sensor
7- LED to signal the network connection and other functions
8- I/O PIC uC interface
9- Buzzer
10- LP2951 Micropower Voltage Regulators
11- 150 mA, 100V Step-Down Switching Regulator
12- Quartz 8MHz for uC

2.2 Test of the circuit for measurements of voltage and current

In a PV module, the nominal values of the voltages are the order of tens of volts and currents are the order of several Amperes. For example, for a PV module with maximum power Pm=200W, Vpm = 55.8V and Ipm=3.59A; the open circuit voltage Voc=68.7V and the short circuit current Isc=3.83A.

The WSN node has been designed for voltages from 9 to 81V and current from 20mA (no-load current drawn from the circuit) to 7A measured with a load of 42 Ohms

In Table B it was expressed in the correspondence between the analog voltage and current values and the corresponding hex values in the registers (S12 and S13) of the ETRX2, after converting A/D; we added the column of the corresponding decimal values.

To test the circuit and for Table B we used a regulated power supply from 0 to 30 V; the higher values were obtained by linear interpolation.

From the measurements, given the substantial linearity of the voltage sensor, we can calculate the linear regression, which is:

$$y = 0.067 \cdot x + 0.75$$

where x is the decimal value in mV, and y is the value of the voltage V, for example setting x to the maximum permissible value in register S12, equal to 1200 mV, the maximum measurable value is 81.85 V.

Similarly, for the current (Table C), from the measurements done it can be deduced the linear regression:

$$y = -11.99\, x + 7126.62$$

where x is the decimal value in mV read on the S13 register and y is the corresponding value of current in mA. For example, setting x to the maximum permissible value in the register, equal to 0mV, it comes out that the maximum measurable value is 7.1 A.

3 Software

3.1 AT Commands

Figure 6 shows the network management; the software of data acquisition has been made on a wireless network with 5 nodes, one of which connected to the serial (USB) input of the PC. For the serial connection it has been used a development board provided by Telegesis, which uses the same module ETRX2: for USB communication with the development board it has been used Microsoft HyperTerminal with commands in the typical AT format of the modem.

The wireless nodes are powered by power supply to simulate the PV module of which you want to measure voltage and current.

AT-style commands provide the tools needed to set up and manage a wireless meshed network, allowing an easy access to low-level functionality of the stack as the communication channel and power level of the transmitted signal.

The parameters that define the functionality of the WSN node (status, in/out, counters, routing, etc.) are saved in the so-called 52 S-Registers, largely non-volatile.

Overall, AT commands and content of the S-Registers are used to control the transceiver ETRX2; the identification address of the node network (IEEE802.15.4 address) consists of 16 hexadecimal digits (64bit EUI64). In Table D we list some of the most-used AT commands. We list some simple examples:

ats00? Views the content of the register S00
ats00=FFFF Assigns the FFFF value to the register S00
ats00A=1 Set the value 1 in the bit 10 (hex A) of the register S00
atsrem00:000D6F0000353F0B? Views the content of the register S00 of the remote node
atsrem00:000D6F0000353F0B=FFFF Assigns the FFFF value to its register S00
AT+SN (Scan Network), lists the EUI64 addresses of the nodes of the net (5 FFD, in this case):

FFD:000D6F0000354047
FFD:000D6F0000353ED9
FFD:000D6F0000353EC5
FFD:000D6F0000353F0B
FFD:000D6F0000353F91

In addition to the AT-like commands, the S-Registers contains some built-in features that can be activated by external interrupt or counters, which are encoded with 4 hexadecimal digits: for example "0101" means "the node sends the contents of the I/O registers of the two analog inputs to the collector node network (Data Sink)".

3.2 Mode of communication

There are three modes of communication between the nodes: Broadcast, Unicast, and S-Cast; the S-Cast mode was used to send the data collected by the sensors over the network to a central data collector node called "Data Sink" (Figure 6). Any node can be choose as "Data Sink", by setting to 1 the 8th bit of its S06 register, but must be unique on the network.

To send the data to the Sink, each node of the network must know its address. This can be done by searching the Sink with the command "AT + SSINK" (scan sink) or, alternatively, the Sink can make the other nodes to know its service by sending the broadcast message in regular time intervals.

If the Data Sink is known, the command "AT + SCAST: <data>" sends a message to the Data Sink which returns "ACK" or "NACK" as in a unicast transmission.

3.3 Data acquisition

Every form has actually three volatile S-Registers, which represent the current state of its I/O:

S0D Defines the Data Direction of each pin: 1 = Output 0 = Input
S0F Output Buffer
S11 Input Buffer – e.g. Reed Switch
S12 A/D1 - hexadecimal value of Voltage
S13 A/D2 - hexadecimal value of Current

It is important to note that the data collected in the input buffer and the analog voltage and current are read in the registers S11, S12 and S13 of each node and can be sent in S-Casts mode to the Sink.

The mode is the one in which a remote node transmits the data from its sensors to the local node (Data Sink), passing through several routers, one connected to each other.

The node can be a SED (Sleepy End Device) operating in power mode 2 with very low consumption (I = 0.7mA) and therefore can be powered by a battery.

- On the remote node it was used the S1F timer of the ETRX2 set for one minute (AtS1F = 00F0): 00F0x250ms = 60sec
- It was chosen the built-in function "0101" in the S20 register, corresponding to the S1F timer (AtS20 = 0101): "The node sends the contents of the input buffer (S11) and of the two analog inputs (S12, S13) to the Data Sink and the timer is restarted;
- The timer causes the node to send its informations periodically;
- The local node (connected to the PC via USB) was assigned as data collector, by setting the 8^{th} bit to 1 on the register S06 (ATS068 = 1).

What one gets on the serial port of the local node is a sequence of strings of type SDATA as follows:

SDATA:000D6F0000353F91,0FE6,00A7,00E6
SDATA:000D6F0000353EC5,0FF7,00B2,00E7
SDATA:000D6F0000353F0B,0FF7,00A3,0237
…

3.4 Application software on PC

For the application, the software was developed in Visual C##, for data acquisition via the serial port of the PC; the strings, besides the identifier of the type of data (SDATA), contain the EUI64 address of the node that sent the data, the 16-bit digital I/O, the two analog input voltage and current expressed in hexadecimal value.

These data, together with the date and the time, were stored in a structured database in order to create a single file for each PV module for each year. For example, the following name:

2010.000D6F0000353F0B.data

indicates the file containing all the readings of the year 2010 of the node with address 000D6F0000353F0B;
the records within it are of the following type:

08-01;06.27.00.985;453;594;0
08-01;06.27.10.629;454;594;0
08-01;06.27.20.535;454;594;0
…

Where “08-01” means the date (August 1), "06.27.00.985" indicates the time (in this case the data are collected every 10 sec.) "453" indicates the voltage value in decimal, "594" indicates the current value in decimal, “0” 16-bit hexadecimal value (0000) show the I/O channels.

In Figure 7 it is shown the interface developed in Visual C##: in the left window it is possible to choose what network node to display, in the graph are represented on the left the values of the voltage (10-90V), on the right the values of the current (0-8A), below are represented the eventual digital I/O, at the bottom you can set the parameters of the serial port to be listen to, the one that is connected to the “Data Sink”.

At the top it is possible to select the mode of reading the data:

- [Current time]: Allows you to plot the values in real time after you start listening to the serial port with the “start” button.
- [Previous hour] [Today] [Yesterday], [past week], [last 30 days] to extract the historical data from the database and obtain a detailed analysis of energy production.

4 Conclusions

The research carried out in this article opens several doors to future developments, especially if there are companies willing to invest in PV modules or to participate in European funded projects. In particular, we think of application software for a complete supervision of the PV plant both locally and remotely, operating virtually in Real-Time for the following operations:

- Supervision, Control and Data Acquisition (SCADA) of the sensors through the network (Figure 8);
- Display of the geometric map with the location of the nodes;
- Graphic display and reporting of data in real-time;
- Management of events (faults, failures, theft, etc.);
- Management of the WNS, intervening on the properties of nodes;
- Access to historical data of the network for date/time, PV module, string, inverters, PV field:

5 References

[1] Telegesis: manufacture of a full range of ZigBee modules complete with full AT command layer giving fast and simple ZigBee implementations.
http://www.telegesis.com/support/document_centre.htm
ETRX2: ZigBee Module Product Manual, Technical Manual, Firmware R2xx User Guide, AT-Command Dictionary.

[2] Telegesis: manufacturer of a full range of ZigBee modules complete with full AT command layer giving fast and simple ZigBee implementations.
http://www.telegesis.com/support/document_centre.htm
ETRX2: ZigBee Module Product Manual, Technical Manual, Firmware R2xx User Guide, AT-Command Dictionary.

[3] Ember: promoter of the ZigBee Alliance that supplies physical layer and ZigBee solutions compliant to the IEEE 802.15.4 standard.
http://www.ember.com/products_documentation.html

[4] ZigBee Alliance: association of companies working together to enable reliable, cost-effective, low-power, wirelessly networked, monitoring and control products based on ZigBee standard.
http://www.zigbee.org/Products/DownloadZigBeeTechnicalDocuments.aspx

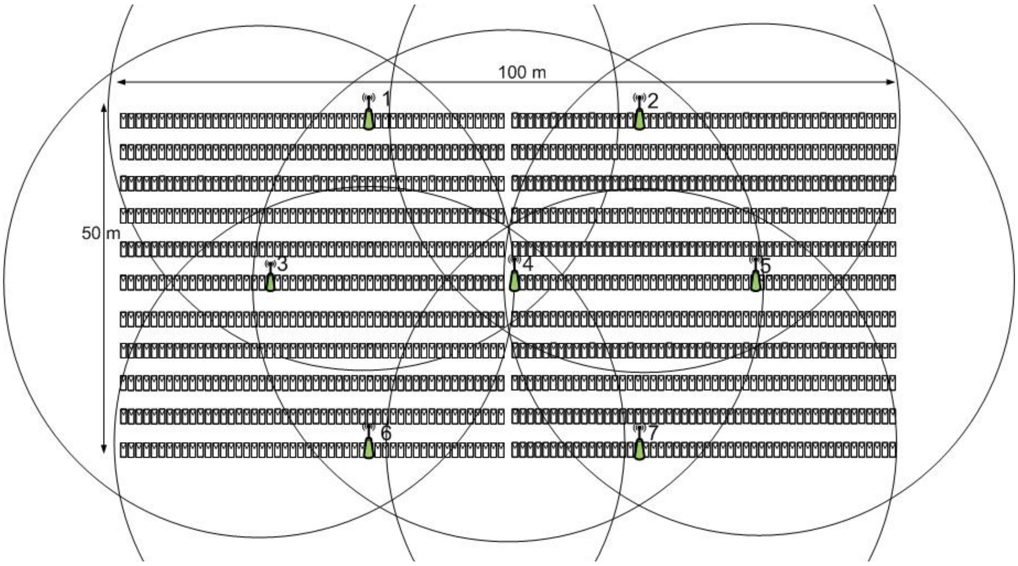

Figure 1. Example of router arrangement with range 30m in a PV plant of 100m x 50m

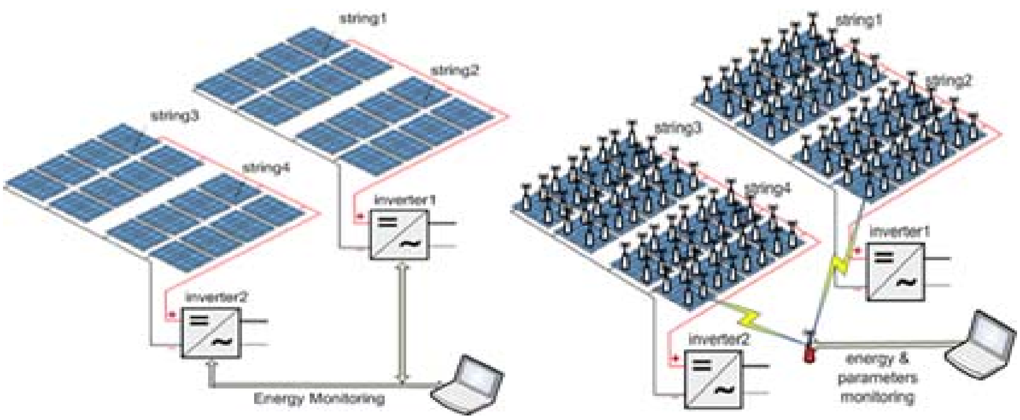

Figure 2. Monitoring on inverter vs monitoring on PV module

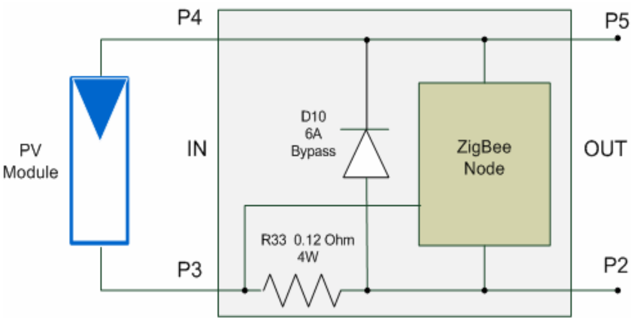

Figure 3. ZigBee node and PV module connection; R33(shunt), D10 (Bypass Diode)

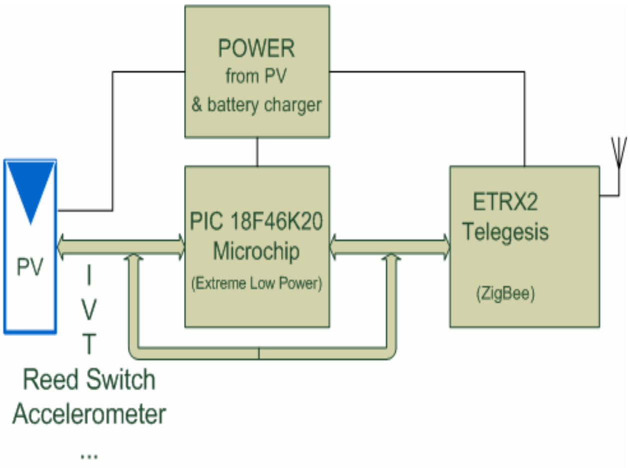

Figure 4. Block Diagram

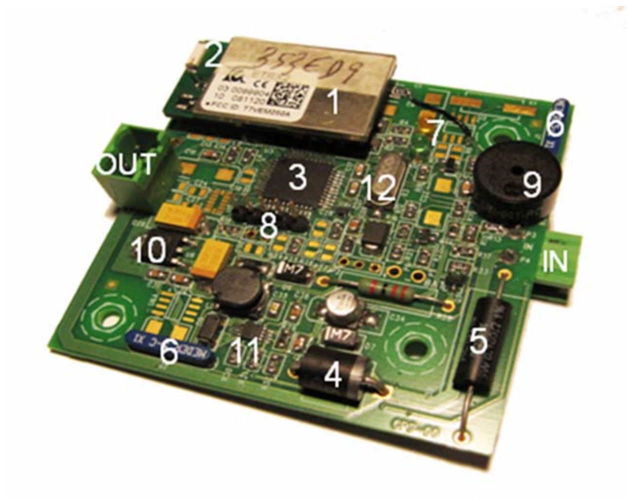

Figure 5. Hardware of ZigBee WSN node

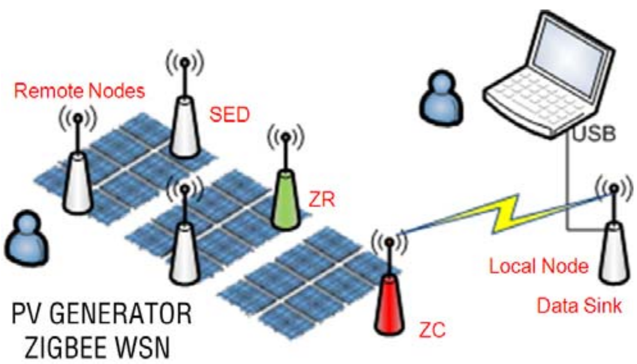

Figure 6. PC connection, and ZigBee-WSN management

Figure 7. PC Interface; Voltage / Current values plotting for [actual hour] and [yesterday] options

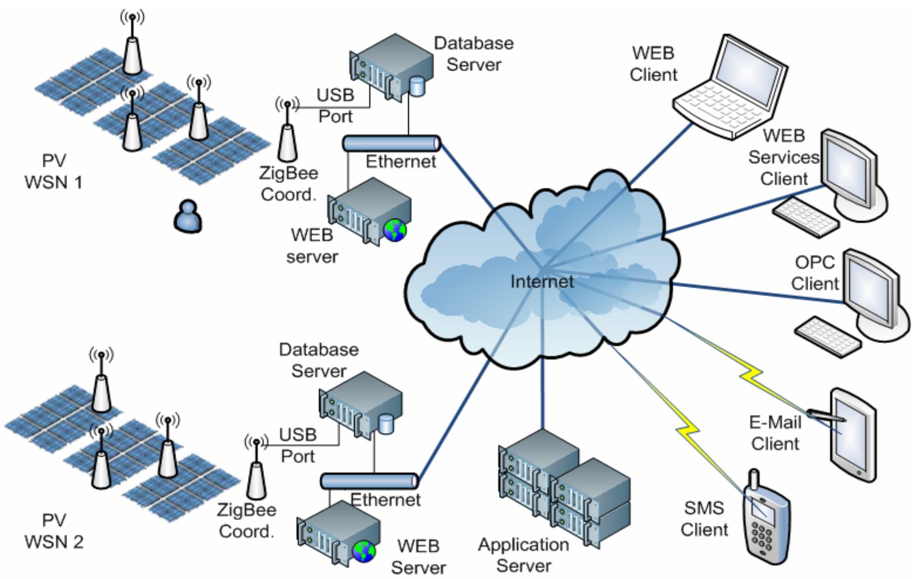

Figure 8. Monitoring of remote systems in different geographic areas

IEEE 802.15.4 Standard Co-existence Features:

Complementary Channel Mapping
Direct Sequence Spread Spectrum (DSSS)
Frequency Division Multiple Access (FDMA)
Low Data Rate (250Kbs)
Carrier Sense Multiple Access (CSMA)
Ultra low-power digital radios based
Long battery life with low latency available
Ability to remain quiescent for long periods without communications
License-free frequency band. 2.4 GHz

Additional ZigBee Co-existence Features:

Network Formation Procedures – (Self-organizing and Self-healing dynamic mesh)

Secure networking (Autentication and public key cryptography)

Mesh Networking and Path Diversity

Network-Layer Frequency Agility

End-to-End Acknowledgement and Retransmission

Table A - Wireless sensor network IEEE 802.15.4 standard features and ZigBee additional features

V [V] y	A/D1 [mV] x	V hex Reg. S12
10	136	0088
15	208	00D0
20	292	011A
25	357	0165
30	431	01AF

Table B - Correspondence between the output voltage from the module and the value in S12 register

I [mA]	Ro [Ohm]	A/D2 [mV]	I hex Reg. S13
0	∞	590	024A
-290	42	570	023A
-392	42	562	0232
-503	42	552	0228
-604	42	544	0220
-700	42	536	0218
-7126	42	0	0000

Table C - Correspondence between the output current from the module and the hex value on the register S13

ATI	Display product identification information of local node
ATS	S-Register access
ATSREM	S-Register remote access
AT+EN	Establish PAN
AT+JN	Join next best network

AT+JPAN	Join specific PAN
AT+DASSL	Disassociate local device from PAN
AT+DASSR	Disassociate remote device from PAN
AT+NTABLE	Show the neighbour table
AT+N	Display network parameters
AT+SN	Scan network for other nodes
AT+SCAST	Transmit data to the Sink
AT+SINK	Display the local Node's sink

Table D - Main AT Commands used to manage network