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Original citation & hyperlink:
Lu, X. , Wang, S. , Li, W. , Jiang, P. and Zhang, C. (2015) 'Development of a WSN based real time energy monitoring platform for industrial applications' in Proceedings of the 2015 IEEE 19th International Conference on Computer Supported Cooperative Work in Design, CSCWD 2015 (pp: 337-342). IEEE
http://dx.doi.org/10.1109/CSCWD.2015.7230982

ISBN 978-147992002-0
DOI 10.1109/CSCWD.2015.7230982

Development of a WSN based real time energy monitoring platform for industrial applications

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Abstract— **In recent years, with significantly increasing pressures from both energy price and the scarcity of energy resources have dramatically raised sustainability awareness in the industrial sector where the effective energy efficient process planning and scheduling are urgently demanded. To response this trend, development of a low cost, high accuracy, great flexibility and distributed real time energy monitoring platform is imperative. This paper presents the design, implementation, and testing of a remote energy monitoring system to support energy efficient sustainable manufacturing in an industrial workshop based on a hierarchical network architecture by integrating WSNs with Internet communication into a knowledge and information services platform. In order to verify the feasibility and effectiveness of the proposed system, the system has been implemented in a real shop floor to evaluate with various production processes. The assessing results showed that the proposed system has significance in practice of discovering energy relationships between various manufacturing processes which can be used to support for machining scheme selection, energy saving discovery and energy quota allocation in a shop floor.**

Keywords—Wireless sensor network; energy monitoring; sustainable manufacturing; Cloud service

I. INTRODUCTION

To date, in a world of rapidly rising energy costs and dwindling the scarcity of natural resources have created strong incentives for energy conservation in the world, especially for the industrial arena where enormously growing demands associated with the more and more stringent environmental regulations and environmentally aware customers have eventually stimulated a focus on achieving energy sustainability in the shop floors. Obviously, the traditional tactical approach of replacing energy inefficient equipment in a shop floor cannot meet the extensive requirements of extracting maximum financial and competitive benefit from energy. Normally, integrating an effective energy management strategy, which requires knowledge about energy consumption as a function of variety machining processes, in a shop floor to eliminate waste and to improve the existing operating procedures is vital for achieving sustainable manufacture. However, neither the machine documentations nor the existing theoretical analysis methods [1] could provide a reliable estimation of energy consumption under diverse machining conditions. In contrast, numerous researches reveal that a real-time energy monitoring system, which could provide a feasibly capability to correlate the energy usage with the machine operations being performed in a shop floor, is a prerequisite component to develop an effective energy management strategy. Furthermore, an efficient energy monitoring system should have capabilities such as continuously automatic energy monitoring to ensure sufficient energy data to be gathered in real-time along with the factors such as cost effective, accuracy, robust and flexibility. Nowadays, the lack of on-site real-time energy information acquisition system to deliver historic and predictive energy intelligence in the traditional manufacturing process has directly reduced the manager's ability to deal with uncertainty of production problems that lead to inefficient manufacturing. Therefore, it has been necessary to make notable efforts in this area to develop an appropriate real-time energy monitoring system for manufactures.

Recently, some commercial off-the-shelf energy monitoring systems [2-3] presented on the market to response this trend by offering a feasible solution to address energy issues in the industrial shop floor. But most of them are expensive and required manual approach to record the data that could be cumbersome for a simple system application and impossible for using in more complicated and bigger industrial applications. Additionally, regarding the manufacturing processes, the average duration of the production activities is calculated in minutes or even in seconds, but the periodic reports from these products that only allow the user to gather the detailed information usually reported daily or even weekly. This is not conductive to the production manager who wants to make effective decisions for managing production lines in real time. In the last decade, more and more scientific researches have been stepped into this area and devoted their efforts from both theoretically and practically to analysing energy consumption of the machines. From the theoretical perspective, numerous researches [4-6] have been conducted to develop devise methods for understanding and characterizing the energy consumption of machine tools during various types of manufacturing activities by using empirical analysis models. These studies [4-6] were primarily used a roughly theoretical estimation approach which hardly provides a reliable estimation of energy consumption under dynamic machining conditions. This made more and more researchers turned to use a practical way by development of a solid hardware platform to obtain energy information from the machines. In order to overcome the intrusive installation problem with the existing wired energy monitoring systems identified earlier, a wireless solution, which promises more feasible for the industrial applications, has drawn more attentions. In recent years, the emergence of advanced computing and Wireless Sensor Network (WSN) technologies provide potential for developing a real-time automation monitoring system for smart manufacturing. Currently, some automatic monitoring systems based on these ubiquitous technologies have been extensively explored. [7] presented a WSN based smart metering system for monitoring energy consumption of buildings. But the smart metering system can only collect energy data from the entire shop floor or building perspective that scarcely possible to give any detail information about energy consumption about a machine. Thus, a machine/equipment level energy monitoring system is imperative. Some researches [8-10] emerged in this area where low-power, low-cost WSN technologies based monitoring systems with different types of sensors have been developed for heterogeneous industrial applications. But none of these platforms have considered to integrate the wireless technologies with other advanced communication technologies such as cloud and Ethernet/Internet/Web service. This makes the solution lack of compatibility and interoperability. Moreover, as stated in [11], despite the use of wireless technologies within industry has been actively explored over the past ten years, application development for industrial is still challenged. Some trade-offs between the system performance and user's requirements should be considered for implementing system in a harsh industrial environment. Despite all the existing efforts, standard solution for industrial applications has not been found.

This paper presents the design, implementation, and testing of a novel, stand alone, accurate, low cost and flexible remote energy monitoring system for industrial shop floors based on a hierarchical network architecture by integration of WSNs with Internet communication into a cloud based knowledge and information service platform to support energy efficient sustainable manufacturing. There are several advantages of adopting this design. Firstly, the hierarchical architecture reduces the system complexity and lower fiscal costs by integrating the cloud enable service platform where experts' knowledge and services provided by other partners could be shared through it. Secondly, the system is flexible and scalable by employing the integration of the advanced WSN with Ethernet/Wi-Fi technologies which allows additionally heterogeneous sensor nodes or systems designed by multiple vendors to be securely and safely added to the network with the minimum amount of effort. Thirdly, the user friendly and intelligent visual interface gives users a convenient feasibility to view and understand their electrical usage patterns with various machining processes in real-time. For further justifying the feasibility and effectiveness of the proposed framework, comparative experiments with commercial products are evaluated at the laboratory and in a real shop floor. The reminder of this paper is organised as follows: Section 2 describes the architecture of the proposed system. Section 3 describes the development of the system. Section 4 provides a discussion of the system evaluation and Section 5 provides a conclusion.

II. System Architecture

This section describes the conceptual design of the proposed industrial energy monitoring infrastructure, as depicted in Fig.1, developed according to a hierarchical network architecture by seamlessly integrating WSN, Internet, Java, MySQL and cloud technologies without a common thread. The hierarchical architecture can be divided into three layers, which are application layer, network and data layer and service layer, according to different functions provided by them.

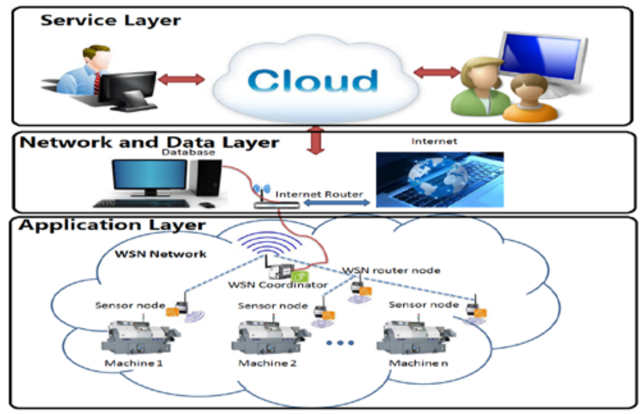

Fig.1 Conceptual Architecture Overview

The application layer is the bottom layer faced to provide basic monitoring information to the upper layers. In order to minimize the system cost from firmware, implementation and maintenance perspectives and meanwhile to maximize the system flexibility and availability to support heterogeneously industrial application scenarios along with different design requirements and limitations, WSNs, which have been proven as the promised ubiquitous technologies to develop a low-power, low-cost, and flexible information acquisition system, are employed in this layer to form the monitoring infrastructure. In order to take advantages from the features offered by the IPv6 protocol and the 802.15.4 compliant WSN, Internet Protocol version-6 Over Low Power Wireless Personal Area Network (6LoWPAN) stack that allow IPv6 packets to be sent to and received from over 802.15.4 based networks, is selected to develop the WSN system in this work. The general architecture of 6LoPAN WSN is depicted in Fig.2. A variable number of sensor nodes of different types with extended capabilities to sense information from the physical environment can eventually cooperate to form a WSN via a network coordinator, whose main responsibilities are to create and maintain the WSN. Due to all communication between end devices to the upper layer components propagates through the coordinator, it can be seemed as a network bridge or gateway to bridge communication between the WSN to Internet.

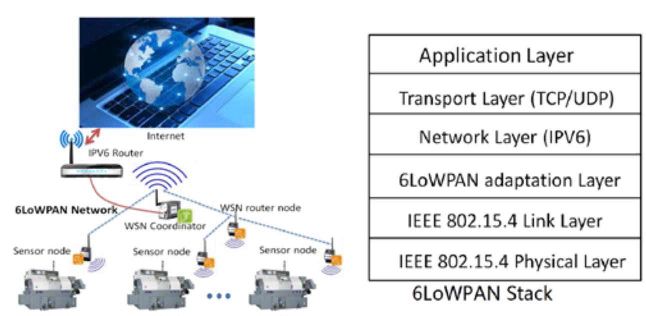

Fig.2 6LoWPAN based industrial WSN

The network and data layer is the middle layer which comprises a service oriented data server and an IPv6 Internet router. There are several reasons to adopt the existing Ethernet infrastructure as a backbone to support WSNs. Firstly, the hybrid network design by integrating low data rate WSNs with a relatively high data rate Ethernet/Internet standard can maximally utilize advantages of these two technologies to adapt applications, which have diversified data communication requirements. Secondly, the wide spread presence of Wi-Fi or Ethernet infrastructures in industrial sectors could bring benefits to rapidly form a comprehensive energy monitoring system. As stated in [11], several industrial wireless standards have been emerged for various industrial applications. The Ethernet router is an ideal solution to be configured as the backbone among heterogeneous sensor systems and get them connected. The database is responsible for storing, managing gathered sensory data and providing real-time visual interface to end users.

The top layer is named service layer, on which the cloud enabled knowledge and information service platform is integrated with providing the functions such as data sharing and analysing, energy efficient process planning and scheduling, and machine energy consumption model establishing. The big advantage of using cloud technology is that it provides capability for extracting and mashing up of heterogeneous sensory data using artificial intelligence and human expertise in creating effective, efficient, knowledge based intelligent services to optimise manufacturing energy consumption. In this paper, the cloud based service platform will not be introduced.

III. SYSTEM DEVELOPMENT

According to the aforementioned hierarchical architecture, the system development can be divided into a 6LoWPAN enabled real time energy monitoring system and a Java and MySQL based data server designs.

A. *Real time energy monintoring system development*

According to [11], the characteristics of an industrial WSN should be stable, moderate cost, low installation overhead, easy configuration, plug-and-play and security. Several system performance and parameters are compromised to cater to these design criteria. The implementation of the proposed system is illustrated in Fig.3. As depicted, three types of devices, which are a 3-phases current sensor node, a 3-phase voltage sensor node and a WSN coordinator connected with an IPv6 Internet router, are employed to form the 6LoWPAN network. All these devices are developed on Jennic JN5168 developing kits [12], which offer a powerful AMR core along with IEEE 802.15.4 radio to fully support the 6LoWPAN stack, ZigBee pro and 802.15.4 stacks. In order to provide interoperability between the Internet, based on Wi-Fi or Ethernet, with the 6LoWPAN network based on 802.15.4, the combination of a USB dongle and a Linksys Wireless-N board router supplied from JN5168 developing kits, as depicted in Fig.3, is employed to form the network gateway. In this mechanism, the USB dongle acts as wireless network coordinator to manage the 6LoWPAN Network and meanwhile the board router provides the interface with Internet.

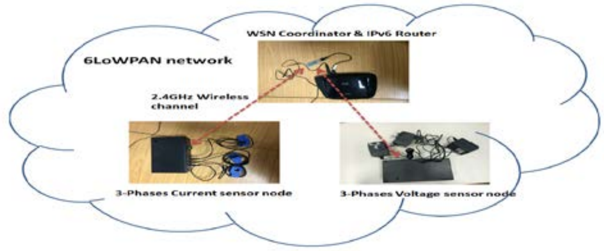

Fig.3 6LoWPAN based energy monitoring system

Every sensor node is normally comprised of four main components, sensing, processing, communication (radio) and power units. In this work, the DR1174 board from the evaluation kit [12] is used as the processing and the communication unit. Due to the sensor nodes which have a wide distribution in an industrial shop floor where the nodes should maintain their functions for a long period, the power supply unit not only determines the lifespan of the module itself but also determines the feasibility of the system. By considering the relatively desired long lifespan and moderate maintenance cost along with the system is placed in context of shop floor with the sufficient energy supply, a replenishable power supply design is considered as the finest solution for this work. By comparing the power availabilities at the shop floor, which are 24V DC, 12V, 24V, and 220V AC, between the power supply options of the DR1174 board, which can be powered from a USB cable, lithium or AA batteries or directly from the 24V DC or 12V AC power, the12V AC power drawn from the power supply cabinet is selected.

Most industrial machines are powered by 3-phase power and 3-phase power equation can be expressed as:

$$P = \sqrt{3} V_{rms} \cdot I_{rms} \cdot \cos\phi \qquad (1)$$

where P, V_{rms}, I_{rms} and $\cos\phi$ are real power, root-mean-square (rms) voltage, rms current, and power factor, respectively. In order to attach manufacturing processes related information to the raw energy data, the system needs to separately measure the input voltage, current, and power factor flowing through the machine with fabricated sensing modules. From equation (1), the power factor, defined as the ratio of true power to apparent power, can be calculated as the Cosine of the phase angle between voltage and current. In order to avoid complex phase angle calculation between voltage and current, a constant 0.83 factor, calculated from the machine specification, is used in this work. For the current and the voltage sensor designs, the sensory signals from the sensors are connected to the ADC pins from the DR1174 carrier board to transfer analogue values to digital readings. In order to accurately calculate the instantaneous power, 3-phase currents and 3-phase voltages need to be sampled respectively and simultaneously. By considering only 4 ADC channels available on the DR1174 board, two separate boards were used in this work to measure currents and voltages separately. For the current measurement design, there are some design criteria which need to be considered. Firstly, since a ADC requires an input voltage instead of a current parameter for its conversion, the current passing through the machine must be converted to a voltage variable to be measured. Secondly, by considering the measurement circuit, which is powered from both 3V and 5V low DC voltages, along with the safety issues generated by using the system in a high voltage environment, the good electrical isolation design is critical. Additionally, to minimize the installation cost and to meet little or no interference with the existing machine, non-contact plug-and-play current sensor is considered as the ideal solution for the industrial application. Hence, a low cost current transformer (CT) sensor SCT-013-000[13], based on Hall Effect, is selected in this work. The power supplied at a shop floor is normally delivered as a 60Hz sinusoidal waveform which indicates a minimum sample rate of 120Hz is required to accurately measure the current through the connected machine, but by examining the specification of the JN5168 microchip, the maximum sample rate could provide by it is around 33Hz which is far below the requirements. Thus an additional circuit is required. A true RMS-to-DC converter AD736 [14] integrated with a negative voltage supplier, LTC1044 [15], are developed to avoid complex RMS calculation on the microchip with a limited computational ability. The principle and the hardware integration are depicted in Fig. 4. The instantaneous current consumed by the machine is measured through the current sensor along with a burden resistor, value depended on the application. The measured voltage is sent to the AD736 chip, in which an AC voltage waveform is converted to a true rms DC voltage output. Finally, the output DC voltage is converted into a digital reading by using the on chip ADC pin and the digital result is propagated through 2.4Ghz radio to the network coordinator.

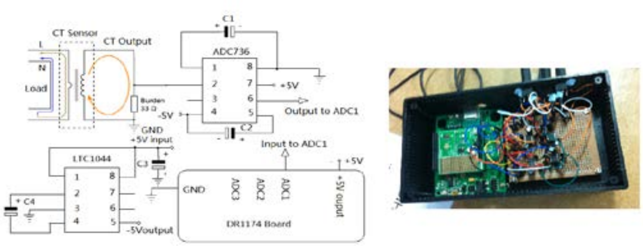

Fig.4 Schematic and hardware design of current sensor node

For the voltage sensor node design, as there is no non-contact voltage sensor available on the market, the price and the simplified system construction are the two critical factors in designing the voltage sensor. A step down voltage transformer, Mascot 9580 AC/AC adaptor from Mascot Ltd.[16], is selected as the voltage sensor in this work to convert input supply of 230-240V to 9V AC signal. In order to transform an AC signal to the DC form, the similar peripheral circuit using in the current sensor node is adopted. The schematic and hardware design are shown in Fig.5. Unlike using the board resistor to adjust output voltage of the current sensor, a potential divider (R1 and R2 in Fig.5), is designed to scale down the output voltage to a proper level for measurement. Moreover, an auxiliary low pass filter capacitor (C5) is connected between the output and pin3 of the AD736 chip to stabilize the output signal of the AD736 chip for ADC conversion. In order to protect sensor motes from the hazardous machining environment, which may contaminate the electrical circuitries, all the sensor motes have been sealed in a fire resistance black box.

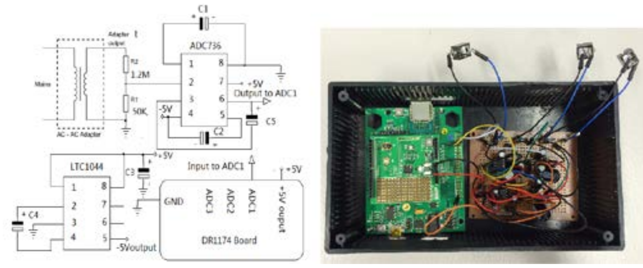

Fig.5 Schematic and hardware design of voltage sensor node

B. *Software design of the data server*

The energy consumption of individual machine and network information of the WSN can be intuitively displayed through the user visual interface in real time. Fig.6 is the screenshot of the developed user interface, which is built on Windows operating system with Java as the programming language and collected data is stored in the database, which is developed through a MySQL platform. According to the figure, the left part shows the current network topology and the right part intuitively illustrate the query of the power and the voltage values of three phases, respectively. Furthermore, in order to provide more flexibility to the end user, some user friendly functions are integrated on this platform. For the security and safety reason, all communication and instructions of new sensor nodes are checked before implementation in the WSN. Once the sensor node is proven and added into the network, the server will record the node's address in an address book. The sensor nodes, whose address have been recorded, can avoid duplicated security checking when they have been rebooted. In order to provide a convenience for data analysis, a chat plot function is implemented on the server. The voltage, current, power and energy data can be plotted into curves or exported in an excel spreadsheets in the form of secondly, hourly, daily, and weekly, respectively, according to the users. Moreover the WSN is subjected to a harsh industrial environment where unpredictable interferences and contaminations might cause the system malfunctioned. In order to incessantly monitor the data receiving from the sensor nodes without any human interference, the automatic network fault diagnosis function with the self-checking and self-healing would provide significantly flexibility to the end users. The principle is that the server remotes reboot any sensor node if data is not received from it in a minute. After rebooting process, if data is still not received, the server considers the sensor node malfunctioned and a network error message will show on the user interface, and the server maintainer will check and reboot the sensor node manually.

Fig.6 User Interface

IV. SYSTEM EVALUATION

The implemented system was evaluated from both quantitatively and qualitatively in order to demonstrate the feasibility and effectiveness. The evaluation processes were split into the following two stages.

A. System calibaration

The small-scale prototype of the proposed system, depicted in Fig.3, has been preliminarily conducted with a table top CNC machine, Syil X4 machine, at the lab in Coventry University, as shown in Fig. 7, by comparing with two aforementioned commercial energy monitoring products, SPcPro [2] and Fluke 125 industrial scope meter [3], to verify the current and the voltage readings, respectively. The assessing results of current and voltage measurements are shown in Fig. 9 (a) and (b) respectively. The results show good correlation between the developed system and these commercial products. Then more tests were conducted in the lab between these systems by using different electronic appliances, such as kettle, microwave, radiator etc., and the comparison results were used to calibrate the sensor readings of the proposed energy measurement system.

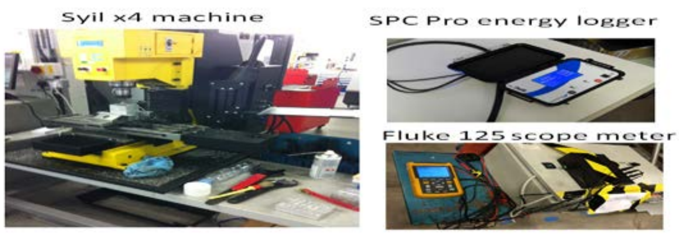

Fig.7 Experimental test at Laboratory

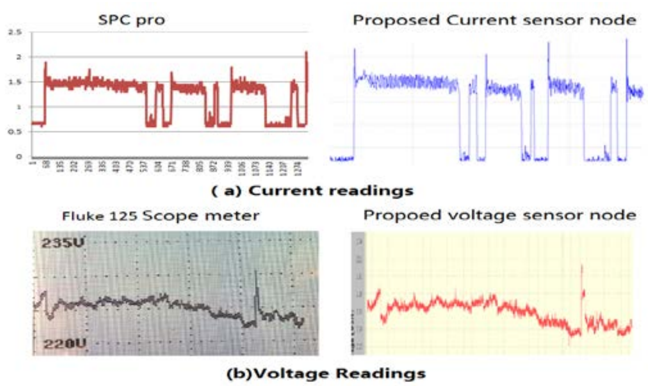

Fig.8 The comparison results of current and voltage measurement

B. System evaluated at real industrial environment

In order to evaluate the proposed system in terms of durability of sensors and reliability of communication under real operational conditions within a hazard industrial environment, the system was deployed with a representative industrial case in collaboration with Swegon Ltd's Kvanum factory at Sweden. The preliminary field deployment consisted of sensors to measure 3-phases current consumptions and 3-phases voltages supplied on Salvagnini S4Xe punching & shearing machine. Due to the system is subjected to a real industrial environment, some design requirements and criteria that should be considered before it being implemented. Firstly, according to the S4Xe machine, whose has 44A nominal current and 25kW nominal power, 20Ω the burden resistor of the current sensor, depicted in Fig.4, is selected to adjust a proper signal for current reading. Secondly, ensuring the monitoring system can capture energy pattern to reflect the rapidly punching and shearing processes, which normally last for one second, the current sensor node was designed to read each sensor channel four times per second. Due to the low data-rate limitation, a trade-off between to grab sufficient energy data for data analysing and to reduce the wireless communication burden for achieving the high system reliability is considered and only one equal value of the four sensor readings, measured in a second, is transmitted to the coordinator in every second. Thirdly, the proposed system must coexist with the existing heterogeneous networks and systems in the shop floor. By investigation the 2.4Ghz wireless patterns in the shop floor, all the 2.4Ghz Wi-Fi channels are occupied by their production systems. Channel 20 of the 802.15.4 standard was selected in order to avoid the unforeseen interferences between the existing wireless systems. For further reducing the possibility of the inference caused by proposed system, a low power JN5168 module with an integrated antenna associated with 0dBm transmit power was adopted in this application. In order to guarantee the data transfer reliability of the proposed energy monitoring system in the shop floor, two DR1174 boards, programmed with a packet error rate testing code developed on the 802.15.4 network stack, has been tested in the factory before the proposed system was implemented. The results show that a good communication quality can achieved when the sensor nodes was placed less than 15m away from each other. Fig.9 shows the system implementation in the shop floor. As depicted, the data server platform was installed on a desktop, which was securely locked in a metal cabinet placed beside the machine. The combination of the coordinator and the Linksys router was placed on the top of the data server plays as the gateway and all the sensory data it received is handed on the data server through an Ethernet cable. The current sensor node was implemented on the top of the power supply cabinet of the machine, which is 8m away from the data server. Three CT sensors were clamped on the three separated main power lines to monitor current consumption of the machine, respectively. The voltage sensor node, which is used to measure the shop floor voltage supply quality, was installed 2m away from the data server. The proposed system has been continuously operating since October 2014 through extremely industrial environment conditions. The two months experiments showed the correct functionality of the devices 100% of the time.

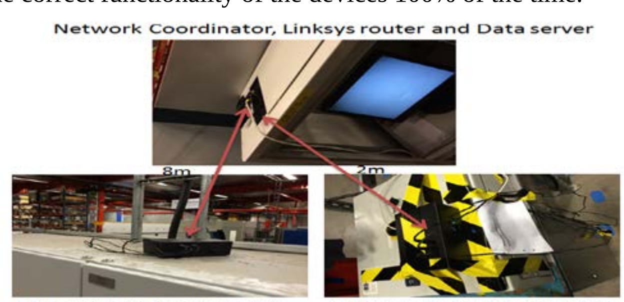

Fig.9 System implementation

A 36 hours power pattern of the machine is plotted in Fig.10 from the database for demonstrating of the feasibility of the revealing relationship between the energy consumptions and machine operation processes. A simple energy analysis was carried out. According to the pattern, the machine start time and stop time of each working day can be recorded and three basis machine states, operation mode, standby mode and switch off mode, can be implied. A simple energy sustainable manufacturing strategy by minimizing the machine to stay at the standby mode can be applied to save energy. By further investigation of the pattern, the system still consumes 2-4KW power when the machine is totally switch-off. This is because an air conditioning system and a material management system (desktop) are still running and drawing energy from the main lines. The evaluation of the field deployment in Swegon shows the applicability of the proposed system with industrial applications. The experimentation highlighted that the proposed system could successfully be used to monitor energy consumption and to draw energy pattern in the system level by using 6LoWPAN communication standard. The successful evaluation in the harsh industrial environment supports and demonstrates the potential of the proposed system to be easily adaptable to other industrial applications. The system also obtained valuable information regarding the ease of installation, maintenance requirements and the total cost of ownership.

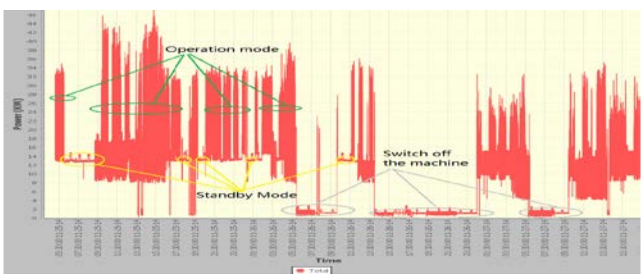

Fig.10 Power pattern

V. Conclusion

In this paper, due to an effective and efficient real time energy monitoring system is imperative required in the modern industrial arena where overwhelming energy issues are faced, and meanwhile the obvious shortages and vulnerabilities of the existing state of the energy monitoring systems using in the industrial sector such as adopting complexity and expense of the architectures, the intrusiveness of the system installations, and the lack of interoperability between different technologies, a user friendly and cost-effective energy monitoring platform based on a novel of hierarchical architecture by seamlessly integrating 6LoWPAN, Ethernet/Internet/Wi-Fi, Java, MySQL and Cloud technologies, was proposed to complement the gaps. The advantages of the platform not only enable the user to monitor electricity parameters of the shop floor at the machine level, it also brings intangibles to the manufactories like understanding the characteristics of their energy consumption, identifying the opportunities to extract maximum financial and competitive advantage from energy and providing a better energy transparency design for customers. The future works focus on cloud enable service platform integration and energy model establishing between diverse machining processes on different machines.

Acknowledgment

This research was carried out as a part of Smarter project, which is supported by the European Commission 7th Framework Programme under grant agreement PEOPLE-2013-IAPP-610675, and meanwhile this research was financially supported by the International Cooperative Project of State Key Laboratory for Manufacturing Systems Engineering in Xi'an Jiaotong University and the National Natural Science Foundation of China [grant No. 51275396].The paper reflects only the authors' views and European Commission is not liable for any use that may be made of the information contained therein.

References

[1] S. Kara and W. Li, "Unit Process Energy Consumption Models for Material Removal Processes," CIRP Annals – Manufacturing Technology, vol 60, pp 37–40, 2011.

[2] SPC Loggers, SPC Pro data logger, http://www.spcloggers.com/downloads/spc-promanual.pdf

[3] Fluke Ltd. Fluke 125 industrial scopemeter, http://media.fluke.com/documents/125_umeng0300.pdf

[4] A.Vijayaraghavan and D.Dornfeld, "Automated energy monitoring of machine tools" CIRP Annals e Manufacturing Technology, vol 59, pp 21-24, 2010.

[5] S. Toenissen, "Power Consumption of Precision Machine Tools Under Varied Cutting Conditions," LMAS Report. University of California, Berkeley, 2009.

[6] T. Devoldere, W. Dewulf, W. Deprez, B. Willems, and J.R. Duflou JR, " Improvement Potential for Energy Consumption in Discrete Part Production Machines," Proceedings of 14th CIRP Conference on LCE, pp 311–316, 2007.

[7] L. Zhao, "Development of a real time energy monitoring platform user-friendly for buildings,"Elsevier journal, Energy and Buildings, Vol 66, pp 41–48, 2013.

[8] W. Sung and Y. Hsu, "Designing an industrial real-time measurement and monitoring system based on embedded system and ZigBee," Expert Systems with Applications, Vol. 38, No. 4, pp. 4522-4529, 2011.

[9] R. Bayindir,E.Irmak, I. Colak, and A. Bektas, " Development of a real time energy monitoring platform, Int J Electr Power Energy Syst, vol 33,pp 137–46, 2011.

[10] A. R. Raut and L. G. Malik " ZigBee Based Industrial Automation Profile for Power monitoring Systems," International Journal on Computer Science and Engineering (IJCSE), vol. 3, no. 5, May 2011.

[11] X.Lu, and W. Li, "A Systematic Review on Industrial Wireless Sensor Networks," to appear in the proceeding of Sustainable Design and Manufacturing, 2014.

[12] NXP LTD. Jennic JN5168 developing kit, http://www.nxp.com/documents/user_manual/JN-UG-3093.pdf

[13] SCT-013-000 current transformer (CT) sensor, http://openenergymonitor.org/emon/sites/default/files/SCT013-000_datasheet.pdf

[14] Analog technology Ltd., AD736 RMS-to-DC Coverter, http://www.analog.com/static/imported-files/data_sheets/AD736.pdf

[15] Linear Technology, switched capacitor voltage coverter LTC1044, http://cds.linear.com/docs/en/datasheet/lt1044.pdf

[16] Mascot Ltd., 9580 AC/AC adaptor, http://www.mascot.no/admin/common/getimg.asp?FileID=1296