The Role of Wireless Sensor Networks for Green Gigabit Access Networks

V. Suraci

Department of Engineering, Università degli Studi e-Campus, Via Isimbardi 10, Novedrate (CO), 22060 Italy; e-mail: vincenzo.suraci@uniecampus.it

Received 17 September 2011; Accepted: 29 September 2011

Abstract

Actual home networks have become an heterogeneous environment in terms of technologies used and do not take into account any intelligent energy saving mechanism. In this paper we propose an energy saving strategy by integrating a Wireless Sensor Network (WSN) with a high speed, hybrid home network. The main objective is to demonstrate that a WSN can act as a dependable control plane, where low data rate control packets can flow even when the high speed home network is shut down. While the home network nodes or some of each node’s network technologies can be deactivate, the WSN is always on and, due to the low data rate required to properly work, it consumes a very limited quantity of energy. This mutual interaction between the high speed home network and the WSN allows at the same time to achieve the convergence of heterogeneous communication technologies in the home environment and leads to a substantial reduction of the energy consumptions. Simulation results show that this strategy is effective in a multitude of scenarios and provides a tangible economic benefit.

Keywords: green, home network, gigabit access, future internet.
1 Introduction

The European countries are facing a hard period since the economic crisis coming from the US has passed the Ocean and has spread into the whole European economic and productive system. To avoid an endless crisis the EU has urgently approved a four years (2010–2013) European Economic Recovery Plan (EERP). The thrust of the EERP is to restore confidence of consumers and business. It is suggested to provide a demand stimulus of €200 billion [1]. The major instrument identified to apply the EERP strategy is the Public Private Partnership (PPP): an industry-driven RTDI initiatives tackling the major socio-economic challenges that look for maximizing EU industrial capabilities in order to allow their best exploitation for the EU industry of tomorrow, enhancing its competitiveness through high impact actions on research and innovation. In particular the PPP on the Future Internet initiative [2] identifies as the most important needs for the research and innovation green technologies and gigabit ICT for all the European citizens.

Recent publications [3–7] show that the ICT industry energy need is increasing with an exponential growth and it is about to exceed than the aviation industry. Thus the green ICT technologies are an emergent research field that needs pragmatic solutions [8]. While green ICT have been investigated in the context of core and access networks [9, 10], consistent improvements should be still done in the context of residential and office networks.

A study carried out by Gartner in 2007 (Figure 1) shows that the 7% of green ICT power consumption is due to home and office networks. It is a small portion of the whole ICT power consumption. So far systematic and
integrated solutions to green this market sector do not exist. Some isolated initiatives have been taken by the manufacturers to improve the network elements efficiency and to make them more green. However the green ICT problem in home networks has never been faced with an integrated approach.

Today’s homes are equipped with a multitude of devices using several wired or wireless communication technologies forming a heterogeneous network environment. This environment may include distinct technologies such as Ethernet, Wi-fi, Power Line Communications. To improve the network resource exploitation the IEEE 1905.1 Working Group on Convergent Digital Home Network is designing a technology-independent abstraction layer called Inter-MAC. This layer is in charge of control of the hOME Gigabit Access (OMEGA) network and provides services as well as connectivity to a multitude of devices. In [11, 12] the heterogeneous technologies could converge below the network protocol layer by means of the creation of an intermediate layer: the Inter-MAC. While the combined use of heterogeneous access technologies allows the home network to speeds up to 1 Gps without new wires, the energy consumption in high speed home networks remains an almost unexplored field.

In this paper we show how the combined use of wireless sensor network and OMEGA network can be applied for a mutual advantage. The wireless sensor network can rely on the gigabit network facilities when it is powered up. The gigabit network can be activated and deactivated dynamically relying on an always on and energy efficient wireless sensor network.

The article is organized as follows: in Section 1 the research objectives are clearly identified. In Section 2 the overall research methodology is presented, in terms of architectural design of the proposed solution. In Section 3 we describe the simulation environment used to deploy the designed solution. In Section 4 the simulation environment and the related testbeds are described in detail. In Section 5 the simulation results are analyzed critically to verify the proof of concept. In Section 6 some business benefit in terms of Return Of Investment are highlighted. In Section 7 some conclusions with regard to the obtained results and necessary future work are presented.

2 Objectives

In view of the above the following research objectives have been identified:

1. Define an integrated OMEGA-WSN architecture;
2. Define a Green ICT strategy for home and SOHO scenarios;
3. Define a cost model to determine the economic benefits of using green ICT;
4. Setup a simulation environment to test the proof of concept;
5. Gather the simulation results and perform a critical analysis;
6. If needed, identify potential improvements to be perform in future works.

3 Methodology

The Inter-MAC architecture is presented in [13, 14]. It is divided into data plane, control plane, and management plane. Data plane is responsible for transferring the user/application data packets. It manages the packets arriving at a device, both from the upper layer (network) and the lower MAC/LLC layer. Control plane performs short-term actions in order to manage the data plane behaviour. It is responsible for managing the correspondence between the higher layer application protocol requests and the establishment of new connections or paths to the desired destination with the appropriate QoS requirements. Management plane is concerned with long-term actions which describe the behaviour of the device itself.

To be properly managed, Inter-MAC layer uses a layer 2.5 Inter-MAC protocol. Each OMEGA node, equipped with the Inter-MAC layer functionalities sends and receives proper data and control plane frames. The frame format is shown in Figure 2.

To let the OMEGA network interoperate with a wireless sensor network for a synergic cooperation aiming to save energy, a twofold integration is needed. First of all each energy-consuming OMEGA node must be coupled to a wireless sensor node. Consequently the topology of an integrated OMEGA-WSN network is depicted in Figure 3.

The integration must be applied also in the protocol stack as shown in Figure 4, where a ZigBee protocol stack has been used. Thus the Inter-MAC control and management planes must communicate to perform an intelligent energy save and a rational use of the OMEGA network facilities.

More specifically each OMEGA node can communicate to the sensor node its operational status. The following mean operative states have been defined: (i) Transmission/Reception, (ii) Bridging, and (iii) Idle. In the first case the node is actively participating to provide QoS-aware applications to an end user acting as a sender or as a receiver of the flow. When the node is acting as a network bridge, there is the possibility to deactivate the unused network interfaces. When the node is in idle, there is the possibility to switch
The Role of Wireless Sensor Networks for Green Gigabit Access Networks

Figure 2 Inter-MAC frame format and header.

- **Protocol Id**: protocol encapsulated in the frame
- **Flow Id**: flow identifier in the OMEGA network
- **Hop Limit**: avoid loops
- **Sequence Number**: determines duplicates
- **Flags**: mainly used to identify frame type (control or data)
- **Inter-MAC source /destination address**: identify the nodes within the same OMEGA network

Off the whole node in a deep sleep mode. In the last two cases it is possible to save energy, depowering parts of the OMEGA communication systems or the whole node.

As discussed in [15], whenever a new flow must be setup from a source OMEGA node A and a destination OMEGA node B, a broadcast (or unicast) path request control frame is sent at Inter-MAC level, to start up the reactive (or proactive) path selection. The path request control frame flows through the
In case of an integrated OMEGA+WSN network, the above described message sequence must be adapted to cope with the necessity to intelligently activate the idled or partially operating OMEGA nodes. Whenever a source OMEGA node A needs to setup a new flow towards the destination OMEGA node B, the path request control frame is sent to the Wireless Sensor (WS) node A. The WS node A is in charge to send the broadcast path request over the sensor network that will be intercepted by the WSN node B associated to the destination OMEGA node B. Thus the WSN acts as a dependable control plane, where low data rate control packets can flow even when the OMEGA network is shut down. While the OMEGA nodes or the OMEGA node’s network interfaces can be deactivate, the WSN is always on and, due to the low data rate required to properly work, consume a very limited quantity of energy.

When an intermediate WSN node receives a broadcast path request, it activates the OMEGA node and all its interfaces if deactivated, retransmits the broadcast packet (to reach even nodes that are out of range from the source node) and sends an acknowledge packet back to the source WSN node. This awakening phase is needed by the source OMEGA node A to ensure that all the OMEGA nodes are activated when it performs the QoS-aware path selection algorithm to discover the best available path from A to B. Once the path selection solution is known, the OMEGA nodes not involved in the new flow can turn back to their previous idled status. The WSN represents a backup control plane for the OMEGA network able to provide both, a reliable low data rate communication channel and an energy aware protocol to activate
The Role of Wireless Sensor Networks for Green Gigabit Access Networks

Figure 5 WSN topology examples.

dynamically only the OMEGA nodes needed to provide QoS to the running flows.

Not all the WSNs are feasible for a green ICT scope. As shown in Figure 5, there exist three main WSN topologies: star, tree and mesh. These topologies require an increasing amount of energy.

While in a star topology the always on node is the PAN coordinator, in a tree topology the full function device must perform relatively complex functionalities thus consuming more energy than a simple connected WSN device. In a mesh topology all the nodes are potentially full function devices, thus in the worst case the mesh topology is the less energy efficient. Unfortunately in a indoor environment as a home, or a small office, home office, the presence of walls reduces the communication range between the nodes composing the WSN, thus to ensure the maximum level of reliability and availability of the WSN overlay, a mesh topology (e.g. multicluster ZigBee) is highly recommended.
4 Technology Description

To demonstrate the validity of the proposed approach, a simulation environment has been setup. The Modeler OPNET 14.5 Educational Version has been used as network simulator for all the tests. It has been preferred against other solutions (NS3, OMNET) for two main reasons. First of all OPNET natively support the technologies needed to perform intensive tests: Ethernet, Wi-Fi and ZigBee. The PLC channel has been approximated using a statistical approach described in [15]. On the other hand a particularly accurate OMEGA OpNET model was already available [12,15]. As shown in the Inter-MAC layer has been introduced in the OpNET simulator protocol stack as a new component called imac and located between the layer 3 protocol (IP) and the layer 2 protocols (ARP and MAC). As clearly shown in the Inter-MAC is in charge to interface the IP layer with the heterogeneous underlying technologies: wireless LAN (WLAN), powerline (bus) and Ethernet (hub).
The OMEGA protocol stack has been modified to cope with the necessity of interfacing with the WSN protocol stack and to manage the operational status of the connected network interfaces and of the whole OMEGA node. This modification has affected mainly the imac finite state machine definition. As shown in Figure 7 a new status has been introduced in the model: inactive. The inactive status means that the OMEGA node is temporary sleeping and needs to be awakened in order to be operative. This status can be modified only by the associated WSN node that, on the contrary, is always running.

The developed WSN node model is depicted in Figure 8. The control_interface process is in charge to manage the communication with the OMEGA node and to simulate the management and control plane interaction with the Inter-MAC layer. As shown in Figure 9 the following main functionalities are provided by the control_interface process:

- **APP_CALL** – this interrupt is triggered by the OMEGA node control plane. When a new path setup procedure is needed, the OMEGA node invoke the broadcast functionality. The WSN node sends a broadcast wake-up packet over the sensor network. Consequently all the WSN
nodes activate the relative OMEGA nodes. Each OMEGA node switch from the inactive status to an idle status. Once the whole OMEGA network is active, the Inter-MAC layer of the source OMEGA node sends over the OMEGA network a Path request packet to trigger the distributed path selection algorithms.

- **BROADCAST_RX** – this interrupt is triggered when a WSN node intercept a broadcast path request packet. If the relative OMEGA node is inactive an interrupt to the imac process is sent to wake up the OMEGA node or to activate all its network interfaces.
- **IMAC_STATE_UPDATE** – it is sent by the imac process to update the WSN node with the actual status of the OMEGA node.
The Role of Wireless Sensor Networks for Green Gigabit Access Networks

5 Developments

The simulation framework has been used to implement different usage scenarios: home network, Small Office Home Office (SOHO) network and Small Enterprise (SE) network. A typical home network is supposed to have less than 10 connected devices. A typical SOHO network is supposed to have up to 50 connected devices, while a SE network may have up to 100 connected devices. Several topologies have been used in the OpNET simulator to generate the most reasonable OMEGA network configurations.

In order to assess the energy saving due to the combined use of OMEGA and WSN networks, the following assumption have been done on the basis of literature and state of the art search (see [17–20] for more details):

- each OMEGA interface (Wi-Fi, Ethernet, Homeplug) has an average energy consumption of 1.5 W;
- each WSN interface has an energy consumption of 0.25 W;
- an average KWh cost of €0.25;
- an average WSN node cost of €4;
- an average OMEGA node energy consumption of 8 W.

Intensive tests have been carried out for the different scenarios. For each scenario multiple tests have been performed to obtain average results. In each test the overall energy consumption has been evaluated applying three different energy saving strategies:

1. No energy saving – the OMEGA network is operative 100% of the time and no WSN is acting to save energy;
2. Partial energy saving – the WSN can solely deactivate the idled interfaces, but not the whole OMEGA node, which is always operative;
3. Maximum energy saving – the WSN can deactivate the whole OMEGA node when it is in an idle status.

In particular the results have been analyzed in terms of differential benefit obtained applying strategy 2 and 3 against strategy 1. Thus the results represent the real energy and cost saving associated to the proposed solution.

6 Results

As depicted in Figure 10, the more the OMEGA network is used during a 24 hours duty day, the less the energy saving strategies are effective. Nevertheless a more aggressive energy saving strategy can guarantee a result three times better than a less aggressive strategy.

The adoption of a maximum energy saving strategy has its own drawbacks. While an OMEGA node needs less than 1 second to power up and activate a single network interface, it takes from 20 up to 30 seconds to turn on the whole OMEGA node and to become fully operative. Thus the best energy saving strategy must be leveraged with the expected reactive time. Since a unique applicable solution does not exist, a proper policy must be decided dynamically or statically to adopt the most appropriate energy saving strategy.

The efficiency of the proposed strategies can be estimated in terms of relative energy saving. As shown in Figure 10, having as reference energy consumption the values associated to the “No energy saving” strategy, and considering an average network daily use ranging from 12 to 4 hours, the “Partial energy saving” shows an average efficiency ranging from 13 up to 27%, while the “Maximum energy saving” strategy ranges from 37 up to 75%.

7 Business Benefits

Integrating a wireless sensor network in the OMEGA network incurs an additional cost in terms of acquiring the sensor network and of energy spent to supply the sensor network. But this initial additional cost can be paid off from the profit gained by the energy saved in using the OMEGA network. Considering the above described scenarios, assuming an average use of 4
The Role of Wireless Sensor Networks for Green Gigabit Access Networks

Figure 10 The top graph represents the partial energy saving strategy assuming that each OMEGA node is equipped with two interfaces; the bottom graph represents the maximum energy saving strategy.
Figure 11 Cost saving results.
hours per day of the OMEGA network and an average of two interfaces for each node, some business benefits can be clearly quantified.

If the strategy adopted is to switch off only the interfaces of a device in idle state than the additional cost is paid off in a period of 9 months for all cases. The average life of the wireless sensor network is estimated to be approximately 5 years. So in this period the benefits are more effective for the scenario with 100 nodes. This fact is depicted in the top graph of Figure 11.

On the other hand, if the energy saving strategy is to totally switch off the inactive nodes the pay off period is reduced significantly to 3 months. In this case even the benefits for the smallest scenario with 10 nodes are substantial and should not be underestimated.

8 Conclusions

In this paper we considered the problem of adopting green ICT technologies in future home networks. We proposed and evaluated an energy saving mechanism by integrating a wireless sensor network with the OMEGA home network. Our strategy dynamically activates and deactivates the gigabit OMEGA network, by means of an always on and energy efficient wireless sensor network. Simulation results show that this mechanism brings substantial long-term benefits due to the energy saved in the overall network, in different usage scenarios.

As a future goal, a better integration of the two networks can be achieved not only in terms of energy saving but also in terms of data plane in order to obtain a mutual benefit. On the one hand, the wireless sensor network can transmit the control messages by using the OMEGA data plane when the nodes are active, and on the other hand the OMEGA nodes can use the wireless sensor network as signalling plane when their interfaces are powered off.

References

The Role of Wireless Sensor Networks for Green Gigabit Access Networks

Biography

Vincenzo Suraci was born on November 7, 1978, in Rome, Italy. He graduated in Computer Engineering with 110/110 cum laude in October 2004 at the university of Rome ‘Sapienza’. In April 2008 he pursued a Ph.D. in Systems Engineering in the department of Computer Systems Science of University of Rome ‘Sapienza’. Currently he is researcher at the university ‘e-Campus’.

His main research interest is to develop and to adapt advanced control and operational research theories (reinforcement learning, column generation, hybrid automata, discrete event systems) to solve challenging and emerging engineering problems: connection admission control, access technologies selection in multihoming and inter-home scenarios, semantic service discovery and composition, context-awareness, embedded systems security and dependability, critical infrastructure protection, convergence of heterogeneous networks, quality of experience and quality of service regulation, green ICT.

He has a wide experience in the field of applied research. From year 2005 to 2006 he managed the IMAGES project, an integrated project within the CELTIC research programme. From year 2004 to 2008 he managed the DIADALOS I and DAIDALOS II IP projects within the FP6 EU IST research programme. In 2007 he joined P2P-Next, an IP project within the FP7 EU ICT research programme. From year 2008 to 2011 he managed the OMEGA and MICIE IP projects within the FP7 EU ICT research programme. From 2011 he is managing the Future Internet Core Platform research project: FI-WARE.