Energy Efficient IoT-Based Smart Home

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Abstract— **Smart Home technology is the future of residential related technology which is designed to deliver and distribute number of services inside and outside the house via networked devices in which all the different applications & the intelligence behind them are integrated and interconnected. These smart devices have the potential to share information with each other given the permanent availability to access the broadband internet connection. Hence, Smart Home Technology has become part of IoT (Internet of Things). In this work, a home model is analyzed to demonstrate an energy efficient IoT based smart home. Several Multiphysics simulations were carried out focusing on the kitchen of the home model. A motion sensor with a surveillance camera was used as part of the home security system. Coupled with the home light and HVAC control systems, the smart system can remotely control the lighting and heating or cooling when an occupant enters or leaves the kitchen.**

Index Terms— **IoT, Smart Home, Energy Efficient, Multi-band Antenna, HVAC, LED, Compact Printed Antennas, Thermal Management, Energy Efficiency.**

I. Introduction

The concept of "automated home/smart home" was first introduced over 80 years ago, and has been facing different technical limitations since then. Recently, service providers and home appliance manufacturers have launched a new initiative to bring the concept of smart homes to reality [1-3]. This Smart Home initiative allows subscribers to remotely manage and monitor different home devices from anywhere via smart phones or over the web with no physical distance limitations. With the ongoing development of mass-deployed broadband internet connectivity and wireless technology, the concept of a Smart Home has become a reality where all devices are integrated and interconnected via through the wireless network [4]. These "smart" devices have the potential to share information with each other given the permanent availability to access the broadband internet connection. Hence, the Smart Home Technology has become part of Internet of Things (IoT), the wireless sharing of information [5-7].

A new challenge is now present in the design process of a Smart Home. In today's world, the Smart Home is not enough to the environmentally-conscious user, but energy efficiency is a key. The IoT provides a strong tool that not only connects wireless communication devices but wireless sensors for heating/cooling or any needed utility within the house to better manage energy usage as well as enhance the living experience in modern homes.

In this work, a house model is analyzed to demonstrate the comprehensive simulation studies on consumed energy reduction for lighting as well as home cooling and heating. Various Multiphysics simulations were carried out on the kitchen room using ANSYS products [8]. Integration of the different smart technologies is also studied including smartwatch communication with home control unit as an example of customizing the Smart Home for the user-based experience. Camera/motion sensor were used as part of the home security system as discussed in Section II and were coupled with the home light and HVAC control system, introduced in Section IV, to remotely switch on/off the lights and turn on/off the heating/cooling system when a person enters or leaves the room. Finally, the coupling/RF interference (RFI) between the antennas integrated within the house's smart devices within their RF circuitries are investigated as well in Section III. Signal integrity is examined to ensure IoT-enabled devices can communicate seamlessly to execute an energy saving protocol. This protocol turns on the LED light bulb and an actuator to open the HVAC duct damper when an occupant enters the kitchen area and gets sensed by the security/motion sensor/camera. The simulation strategies addressed in this work can be utilized to create a virtual smart model of an IoT-enabled smart home and the fundamental elements. Such computational methodologies can be extended to other home parts and buildings such as warehouses, commercial buildings, stadiums, and shopping malls.

II. In-House Smart Wireless Communication

The IoT relies on wireless communication enabled by antennas. Depending on antenna placement, communication can degrade due to obstructions in the antenna path and multipath signal propagation and fading. Figure 1 shows the complete model of the simulated smart home as well as the kitchen room where the different smart devices are populated. Therefore, it is vital for the integrity of the system to study the fields generated by the different antennas employed by the smart devices: triple band energy control unit (900 MHz, 2.45 GHz, 5.8 GHz) [9], security/motion sensor and surveillance camera (5.8 GHz), LED light bulbs (2.45 GHz), and actuator of the HVAC duct dampers (900 MHz) [10].

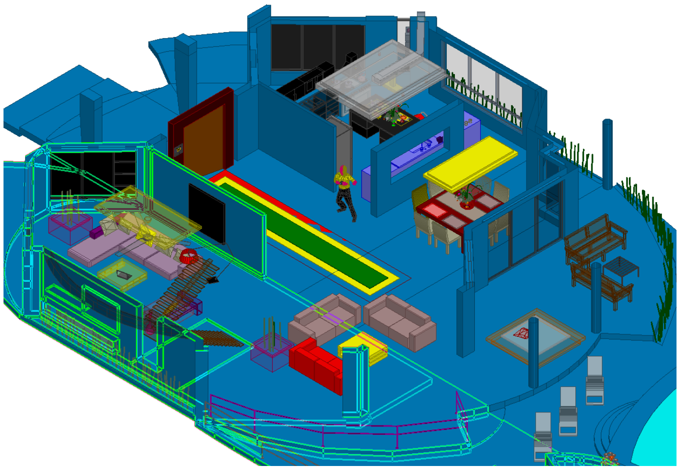
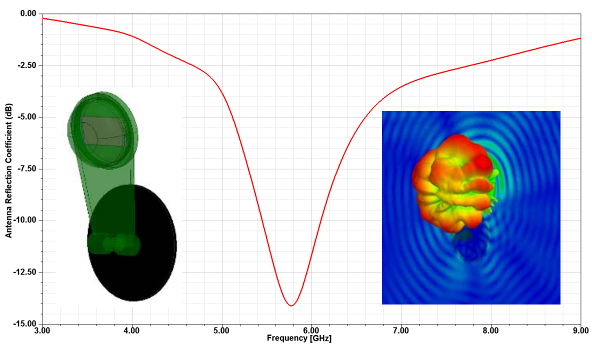


Fig. 1. Simulated Smart Home Model.



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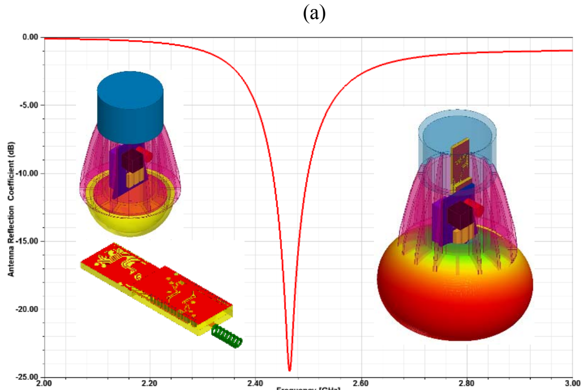

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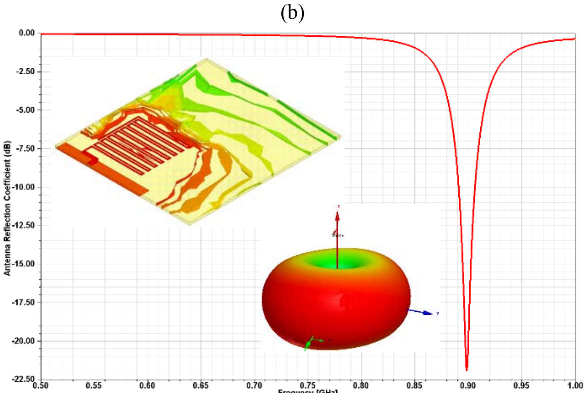
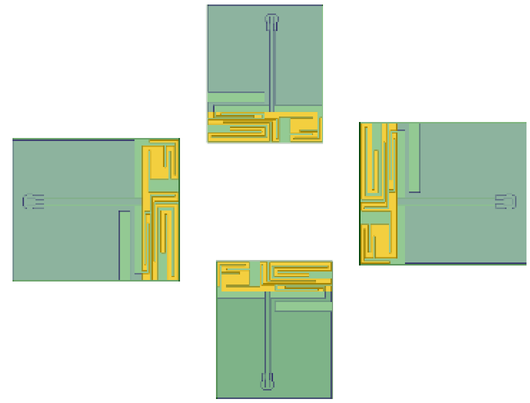


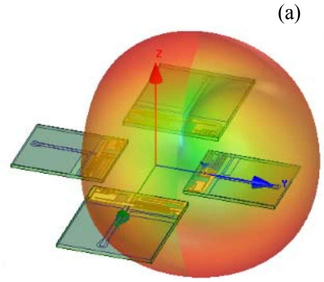
(c)

Fig. 2. Antenna design with simulated reflection coefficient and far field results: (a) Generic motion sensor antenna, (b) Generic light bulb antenna, and (c) Actuator sensing antenna [10].

Figure 2 shows the different antenna models along with their antenna reflection coefficients and far field gain patterns. The energy control unit antenna [9] is designed to cover all three frequency bands as shown in Figure 3. These antennas were designed and simulated using ANSYS HFSS FEM Solver [8].



(a)



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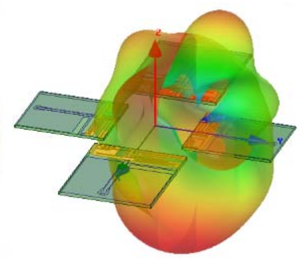

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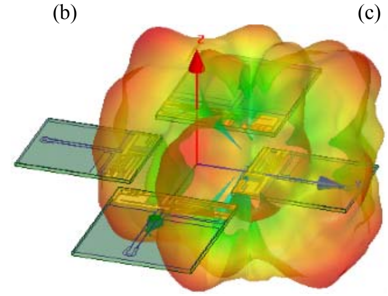


(d)

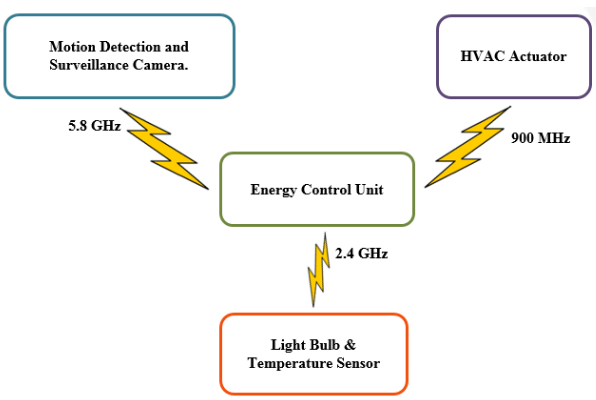
Fig. 3. (a) Triple Band Energy Control Unit antenna model based on [9], Far Field Antenna Gain at (b) 900MHz, (c) 2.45GHz and (d) 5.8GHz.

The suggested modeling scenario starts when an occupant approaches the kitchen. A motion sensor detects this and wirelessly relays this information to the home energy control unit, which turns on LED light bulbs in the kitchen. Temperature sensors that are co-installed in the motion sensor communicate ambient temperature readings to the home energy control unit that remotely turns on or off the HVAC system to regulate the temperature in the kitchen.

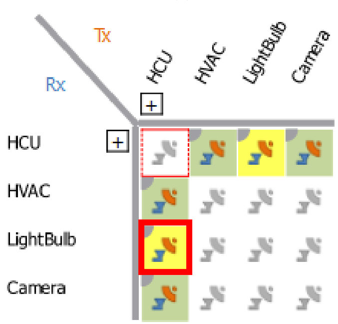
Having modeled the antenna performance, ANSYS EMIT [8] can be used to simulate the performance of the Smart Home's sensors. ANSYS EMIT provides built-in library and behavioral models for the sensors used in the house. In this case, the sensors operate in unlicensed spectrum at the 900 MHz, 2.45 GHz and 5.8 GHz bands using available protocols such as Zigbee [11]. The antenna performance results can then be used with the available RF models to first compute the RF link margin between the sensors and the home control unit (HCU) in the home without any other RF sources. The results are summarized in the Table I. Our target for the wireless system was to obtain a 10dB link margin in this interference-free environment to allow for a comfortable margin. The results show an acceptable 14.6dB link margin for the link between the actuator and HCU. For the motion sensor, the link margin is excessive at 40dB. While this would ensure more than adequate performance for this link, the link is over-designed and changes should be considered to reduce the potential for harmful interference to other links and to reduce power consumption. Finally, the Lightbulb-to-HCU link is only 2.2 dB which, while non-negative, falls short of our 10dB goal. This is somewhat troublesome, particularly in the congested 2.45 GHz band as this link will be particularly susceptible to interference from other sources of RF energy in the home or due to fluctuations in the propagation channel.

TABLE I. SUMMARY OF RF LINK MARGIN BETWEEN THE SENSORS AND THE HOME CONTROL UNIT (HCU)

RF Link	Link Margin (10dB Goal)
Actuator ↔ HCU	14.6 dB
Light Bulb ↔ HCU	2.2 dB
Motion Sensor ↔ HCU	40 dB



(a)



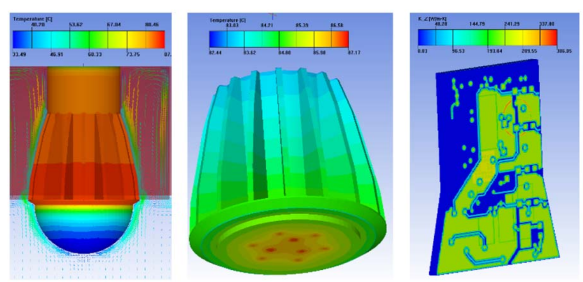
(b)

Fig. 4. (a) RFI Block Diagram with wireless speaker system, (b) ANSYS EMIT Scenario Matrix that represents the interactions between systems and colors them according o performance.

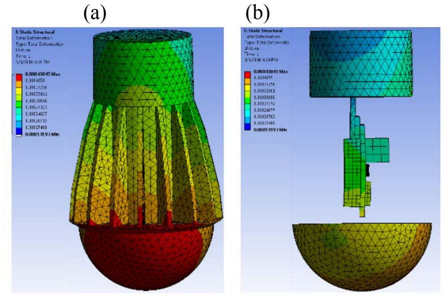
ANSYS EMIT is also used to evaluate the interference from other RF sources within the home. As an example, we can evaluate the impact of a typical wireless speaker system. In this case, we place a wireless speaker that uses a Texas Instruments PurePath^{TM} Wireless Audio chipset in the home as shown notionally in Fig. 4a. The obtained results indicate that the speaker system will cause severe interference to the Light-Bulb/HCU link (red square) in Fig. 4b but will not cause problems with the other links (green) squares. The 21.2 dB *EMI Margin* is severe and requires further evaluation of the RF environment in the home.

III. THERMAL AND STRESS ANALYSIS ON SMART LEDS

Smart LEDs, with an embedded antenna, not only help energy efficiency but also the overall efficiency of the system (home) through wireless communication with other IoT devices. It is important to study the performance of the LED under various operating conditions. At higher temperatures, the antenna's operating frequency shifts from its nominal value due to changes in the PCB's substrate dielectric constant as well as the electric resistivity of the different metallic parts. In addition, thermal stress may cause deformation for both antenna and circuit components causing a drop in the antenna radiation performance. Thermal analysis is performed using ANSYS Icepak [8] on the LED installed in the kitchen ceiling. The LED dissipates heat via conduction to the ceiling, and via natural convection and radiation to its surroundings. The detailed PCB layout is imported for accurate representation of the conduction paths. The computed temperature distribution from the thermal analysis is used to re-evaluate the material properties of the dielectric and conductor materials in the electromagnetic analysis setup. The updated electromagnetic analysis determines a drift in the antenna's operating frequency. The maximum temperature of the LED in this simulation is in line with reported values (by LED manufacturers) for a 13 Watts LED light bulb as shown in Fig. 5.



(a) (b) (c)



(d)

Fig. 5. (a) LED Temperature contour and flow field formation (b) Heatsink and LED sources temperature map (c) PCB thermal conductivity map (d) Total solid deformation.

Additionally, thermal stress and deformation analyses were conducted using ANSYS Mechanical [8]. The total deformation of internal components is computed and verified for structural integrity and performance as shown in Fig. 5d.

IV. Smart Cooling System Controlled By IOT Devices

In this work, a virtual model of flow and heat distribution in the kitchen area of the home with a "zonal" cooling system is demonstrated. A Computational Fluid Dynamics (CFD) model is built using ANSYS FLUENT [8] that includes the ducting from the HVAC unit to the kitchen and its surroundings. In this model, two duct dampers (valves) are considered; the first damper in the vertical duct is slightly open and feeds cool air to the second floor while the second damper is mounted in the horizontal duct and is used to cool the kitchen temperature. The CFD model has a 3.9 million computational grid with polyhedral elements. The grid has two prism layers on dampers, horizontal duct and vanes of the vent. A *k-w* SST turbulence model is used to account for turbulent flow in the ducting and the house. At start time (t = 0 sec), the duct is initialized with a temperature of 55 F, which is equal to the cool air supply temperature from the HVAC unit. The kitchen temperature is initialized with 90 F, a typical room temperature on a warm summer day. The damper opens at the start of the simulation with a speed of 90 degrees/0.5sec (30 RPM). The initial time step of the model is 0.0055 sec (equal to 1 degree of rotation). After the damper is fully open (i.e., t = 0.5 s), the time step gradually increases to capture longer operating times (it takes much longer to stabilize the temperature in the room to a comfortable temperature such as 72 F).

The CFD model in Fig. 6 shows details of flow and temperature distribution in the ducts and the kitchen after opening of the damper.

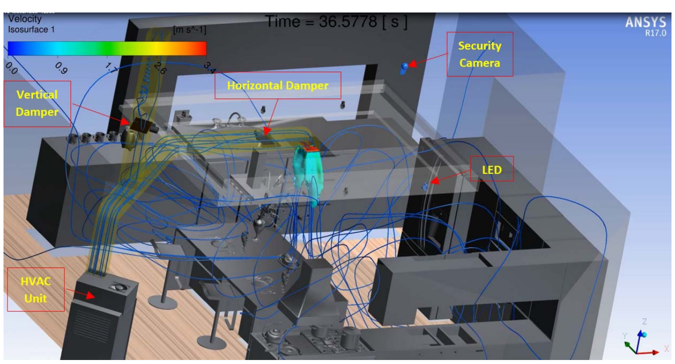


Fig. 6. Flow streamlines in the HVAC ducting and kitchen areas at t = 36.6 sec. A surface in air with temperature of 72 F has been shown and colored by its velocity value.

The streamlines of velocity in the domain at t = 36.6 s show the cold air from the HVAC unit dissipating in the kitchen area. Additionally, a surface in the flow with a constant temperature of 72 F is shown and its color indicates the flow velocity of this surface. This provides feedback on how the room temperature is decreasing to the intended comfort temperature of 72 F. The CFD model outputs can provide valuable insight on the response time of cooling system to zonal damper opening or closing. It can also provide a virtual tool to examine whether this smart IoT based energy control procedure satisfies acceptable limits for temperature, pressure and flow velocity in the ducting and in the living areas.

V. Conclusion

The implementation of the Smart Home devices necessitates the design of the individual units as well as their co-existence within the home environment. Thus, a Multiphysics analysis approach is needed. In this paper, electromagnetic simulation was coupled to thermal and structural simulations to demonstrate the design and tuning of the Smart Home devices in a virtual world. Within the Smart Home, each wireless device has its own antenna module which is designed to ensure that it adheres to specific electrical wireless design constrains. In addition, detailed modeling of the different antennas operating in multiple frequency bands as well as in the diverse thermal and structural environment of the Smart Home was presented. This paper summarizes the antenna module mounted on a smart LED as well as the one mounted on the HVAC system. The ability to control these devices under different environmental scenarios will assist in making the smart home more energy efficient.

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