RESEARCH PAPER

Design for Energy and Electromagnetic Friendly Buildings

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A B S T R A C T:
One of the main issues challenging the building sector is how to reduce building energy consumption while maintaining or improving the quality of the living environment. Therefore, it is essential to investigate a collective design approach to enhance building energy efficiency; indoor environmental quality including electromagnetic and air quality; and wireless connectivity in an enormous range of new frequencies, modulation, and intensities. The objectives of this paper is to develop and verify a triangular concept of “friendly buildings” which incorporates major design and configuration guidance including energy efficiency, wireless connectivity, and electromagnetic environment.

KEY WORDS: Electromagnetic fields; healthy indoor environment, wireless connectivity, energy efficient buildings.

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INTRODUCTION:
Next generations of 5G and 6G systems involving electromagnetic (EM) fields will require a paradigm shift in how buildings are structured and managed. Today, the performance of building design is not fully understood and the construction industries while engaging approaches and technologies for sustainable and energy efficient buildings, do not really consider EM system performance in their designs or specification despite its significant importance for future wireless connectivity as well occupant health. Integration of energy efficiency, connectivity, and healthy indoor environment requires collaboration among experts in architecture, engineering, and health sciences for reliable building design and configuration.

Modern awareness in building performance as a design constraint has developed from an increasing interest in sustainability as a significant socio-economic problem. Beginning with the 1960, architects gradually became more concerned with performance of buildings and their appraisal assessment. The increasing number of sustainable buildings and research projects highlights the area’s growing attention. Today, the trend for building energy codes is to move towards a greater use of building energy simulation and modelling techniques to evaluate building energy performance. Habash et al. (2014) addresses the role of a range of technologies, systems, and solutions with varying degrees of complexity and sophistication in realizing energy efficient buildings.

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An EU-funded project, WIFEEB (Wireless friendly energy efficient buildings) (Altan 2016), sought to develop and verify the wireless-friendly, energy-efficient building concept and to design and evaluate construction materials. The work also aims to show how existing buildings can be reconfigured and how new buildings can be designed. Work involves calculating the energy and wireless performance of a building by assessing the measurements to include both current and future wireless networks and systems. Also it involves analyzing thermal properties of materials, including concrete, brick, wood and plaster (Azambuja 2017). Computer-aided design (CAD) tools are developed and optimized to combine wireless propagation models with energy efficiency models, producing a complete simulation model for the built environment. However, the project does not consider the health and environmental impacts of EM fields on building occupants.

The EM environment can be detected in and around buildings and may cause health effects especially for hypersensitive people when buildings do not comply with adequate protection guidelines. In the environment there are EM fields of different frequencies and at different levels. EM fields are composed first of electric fields (EF) which are governed by voltage, and magnetic fields (MF) which are governed by current. EF and MF are considered extremely low frequency (ELF) fields coming out from sources like transmission and distribution power lines, substations, and home appliances. The second type of EM fields is radiofrequency (RF), microwave and terahertz (THz) from wireless systems including cellular towers, smart meters, and WiFi spots. It is in the best interest of all parties involved to recognize and mitigate any potential health-related threats that can directly affect or negatively impact building occupants due to the living environment influenced by the building materials, and/or systems operation.

This paper investigates the triangular concept of “friendly buildings” which combines major design concerns including energy efficiency, wireless connectivity, and human health. The main objectives is to provide interior spaces with as much illumination as possible through natural daylighting, reduce electrical loads, maximize energy efficiency by deploying energy efficient systems including heating, ventilation, air conditioning (HVAC) and air quality, and emerging building materials, optimize occupant comfort, enhance wireless connectivity, as well as providing a healthy EM environment through integrating technologies and sustainable design strategies. To promote a healthier living and working environment, levels of EM fields around a building under consideration have been measured to provide a guidance for strategies to mitigate the levels of EM fields.

1. ENERGY-EFFICIENT BUILDING ENVELOPE

The building envelope does not consume energy but considerably involves the energy use of mechanical and electrical systems (Jha and Bhattacharjee 2018). Improvements to building envelope elements are generally referred to as passive energy efficiency strategies. The case chosen to serve in this study is retail/residential building in the city of Ottawa, Canada. Figure 1 shows the masterplan of the entire building complex under consideration. The analysis of the study is performed for one climate scenario representing a climate with a cold winter.

1.1 HVAC Energy Efficiency

HVAC typically contributes about half of the energy consumption of a building. Quantitative and qualitative modeling and simulation in the design process offer a comprehensive new understanding of the different ways to engage with environmental factors. The American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) cover a wide variety of engineering topics and offer valuable design approaches for a safe and reliable building systems operation. They are the most widely promoted guidance for thermal comfort in the form of the ASHRAE 55 standard for thermal environmental conditions for human occupancy (Sailor 2013). While the ASHRAE 62.1 handbook focuses on the basis for adequate building ventilation, ASHRAE 62.2 provides the designer with the specific ventilation requirements related to low-rise buildings which are the example buildings used for this study. The air quality in dense areas surrounding the building is influenced
by the concentration of activity of the local population as well as its surrounding local natural environment. It is therefore required, and in many cases beneficial to provide a means of treated sourced outdoor air while controlling and/or eliminating the entry of dust, pollen, pollutants into the dwelling’s breathing environment. Using natural ventilation in such cases allows for untreated air to enter the dwelling which can reduce the indoor environmental quality (IEQ) of the occupants. With the local climate in Ottawa having winter weather conditions reaching at times below 30°C, and in the summer reaching above 30°C, thermal systems are required in order to comply with thermal comfort standards (ASHRAE 55 and 62.2), and with such a temperature range. The introduction of outdoor air into the living spaces should be minimized during times of extreme weather for the sake of energy efficiency.

Nearly every energy model requires the user to select a HVAC system. The heating and cooling demand is generally driven by the goal of maintaining the occupied space within a comfortable temperature and humidity range as well as adequate air change rates to manage pathogens and dust particulate generated within the living space. The size and complexity of the HVAC system is determined by considering the occupant needs, the capital cost, and the ongoing reliability over time. There are methods used to recover the sensible and in some cases the latent heat from exhaust air in order to pre-heat/cool the incoming outdoor air by means of indirect contact. This lessens the heating requirement for outdoor air and can lead to the selection of a smaller and more efficient system. It also limits the capital cost to a single centralized system opposed to several localized units which simplifies the maintenance and minimizes occupant interruptions. This practice is very common in large buildings settings and is often standard in North-American urban municipalities.

An HVAC system generally contains a source of heating and/or cooling, a distribution system, and a technique for supplying fresh air. These include boilers, furnaces, and/or electric resistance heaters which are typically used to add heat to buildings. Cooling is typically accomplished via air conditioning units, heat pumps, or even via chillers and/or cooling towers. Efficient and effective building operation and maintenance (O&M) is critical in order to meet sustainable operating conditions.

Among building energy services, HVAC systems are the greatest energy consumers, accounting for about 10 - 20% of final energy use in developed countries (Gu et al. 2014). In general, 25% - 45% of energy related to a HVAC system is wasted due to duct and valve leakage; HVAC left on when space is unoccupied; faults due to improper system balancing, software programing, improper control hardware installation, improper control logic and strategy, insufficient evaporator airflow, improper refrigerant change, improper controls setup and commissioning (Akinci et al. 2011). Air filtration can also contribute to unnecessary use of energy if the filter media is seldom replaced or maintained as the pressure drop across a saturated filter can anticipate a considerable air restriction thus making the supply fan work harder to maintain system static pressure.

1.2 Demand-Based Ventilation and Zoning

It is expected that at least 5-15% of energy waste is due to the conditioning of unoccupied spaces. By implementing a multi-zone system in buildings, considerable energy savings can be achieved. One of the goal of this study is to minimize such waste by enabling room-level zoning where each zone is conditioned individually based on its occupancy. This allows only occupied rooms to be conditioned, reserving energy needed to condition unoccupied rooms. However, zoning systems are expensive, and are typically used for much grained zoning of buildings. Such a technique is both spatially and temporally grained, allowing large areas of the building to be zoned separately and scheduled with a low frequency. To maintain an effective ventilation system, ASHRAE 62 provides guidance in monitoring the levels of CO2 of an interior space by providing a means to determine acceptable outdoor air ventilation rates meanwhile the HVAC component is designed according to ASHRAE 52 for meeting space thermal and humidity requirements. By using CO2 as a measure of breathing air saturation, it is desired to maintain certain level of CO2 that is acceptable to mitigate any health-related impacts. Having an
HVAC respond to ventilation air requirements dynamically by maintaining a setpoint based on occupancy demand to a level 1000 ppm or less of CO2 has proven to be the most efficient means of operating a variable flow HVAC system without any impact on the building occupant.

In this study, SolidWorks was used to simulate a multi-zone HVAC system for both the townhome dwellings as well as the midrise dwellings. Each of these zones has its own thermostat, and temperature is controlled independently of the other zones. Figures 2 demonstrates the results when a single zone is activated. The air circulates throughout the main living spaces, which is primarily used during the daytime. As the bedrooms are not typically used during the daytime, their respective zones will remain at a lower temperature setpoint than the occupied areas. Overall, it may be concluded that by dividing the dwellings into three zones for this case, occupant comfort can be increased by individual temperature control. Also, energy is conserved by reducing outdoor air supply to areas that are not occupied at various times of the day and night. In addition, energy savings can be increased if more zones are implemented allowing individual occupants to adjust and even schedule room temperature operating setpoints to maximize their desired comfort efficiently. Occupancy sensing can also provide additional savings where a master switch is activated by either a hand-held device or a key that activates the building systems.

2. FUTURE BUILDING MATERIALS

2.1 Nanomaterials

Building materials of the future are in development today. From graphene to stronger concrete to metamaterials that rethink the form and purpose of typical construction modes with the potential to change architecture. At the nanoscale, quantum mechanical effects come into play to enhance physical and chemical properties such as strength, reactivity, and electrical characteristics. Nanomaterials offer architecture and related disciplines a means of achieving greater energy efficiency and sustainable construction. The newly shaped material, scaling from thermal insulation, fire-proof and anti-graffiti to heat-absorbing and solar protection to EM blocking to antibacterial self-healing and self-cleaning, couple the structural properties of its medium to acquire several characteristics.

2.2 Metamaterials

Over the past several years, new materials called metamaterials (“meta” means above, beyond, altered, or changed) have opened up possibilities for new and innovative functions. Metamaterials can be classified as EM, acoustic or seismic in nanoscale structure, engineered for manipulating waves by blocking, absorbing, or bending. They can be classified on the basis of electric permittivity $\varepsilon$, magnetic permeability $\mu$, and negative refractive index $n$. EM metamaterials have emerged as innovation with a potential to change architecture toward providing management of indoor wireless networking (Savic 2017). They provide invisible characteristics to control waves, such as negative refraction, perfect absorption and transmission, through the periodical arrangement of meta-atoms made by the size smaller than incident EM wavelength (Yannopapas et al. 2009). A basic design consists of an array of electrically small EM scatterers, called inclusions, embedded into a dielectric host material. From the form of their meta-atom design (building blocks at the nano-, micro-, or macro-scale), they are arrays of structured composite materials that can be engineered to have desired EM properties and functions including reflection, refraction, absorption, and polarizations. When treated macroscopically, metamaterials display custom permittivity and permeability beyond those found in natural materials. As a result, metamaterials enable different interactions with impacting EM waves, being able to fully re-engineer received waves.

2.3 Efficient Materials

The importance of material efficiency and the need to improve it can be studied from several perspectives (Ruuksa and Häkkinen 2014). The choice of a given building material may have multiple effects on a building’s energy consumption over the different phases of its life cycle. These effects can be contradictory since properties such as high insulation value may yield relative savings in operational energy together
with higher embodied-energy costs. The balance of these factors is especially significant since a building’s external structure and envelope (roof, floor, walls and windows) tend to account for the greatest portion of its embodied energy (Atkinson et al. 1996).

For this study, thermal modeling is performed using EnergyPlus simulation. Various materials were selected for the building, windows, and roof. Higher performing assemblies with a greater effective R-value are proposed. Wood studs, concrete masonry unit (CMU), structural insulated panels (SIP), insulating concrete forms (ICF) were selected. It is concluded that the energy savings by a window relies not only on the thermal conductivity (U-factor) and the solar heat gain coefficient (SHGC) but also on its orientation, climate conditions, insulation level, floor area, and others.

3. WIRELESS CONNECTIVITY

The propagation of low-frequency wireless is far superior to that at higher frequencies which is an important fact for WiFi and future 5G/6G systems which operate at frequencies above 6 GHz. The key-enabler for building a programmable wireless networks (PWNs) is the concept of metamaterials and metasurfaces (Hang et al. 2016).

To improve the design of buildings and create new constructions, two particular novel structures may be considered: frequency selective surfaces (FSS) building components such as walls, windows and facades; and intelligent walls. FSS are simple printed metallic patterns which can be applied to insulation windows or as standalone panels and act as filters to wireless EM signals allowing some frequency bands to pass while rejecting others, for example passing cellular signals and rejecting WiFi signals. This technique allows the use of metal backed insulation which does not interfere with some of the EM signals while rejecting others. Intelligent walls provide designers with the flexibility to reconfigure a building for different usage to facilitate enhanced wireless connectivity in designated sections of the building.

Architectural design may be used to optimize the presence and distribution of PWNs in buildings. These structures could be designed to reflect EM radiation as Faraday cages, but also to actively change states between blocking and permitting EM waves to pass through them. Architects can account for the use of materials and disposition of routers in a more active manner, resulting in better EM propagation. This requires detailed studies of network propagation. An example is given in Figure 3 which studies a possible EM routing configuration to serve the objectives of the scenario. Blocking signal is owed to material absorption losses, and the natural spreading of power within space, for example, the distribution of power over an ever-increasing surface. Multiple 2D metasurfaces are engaged to coat objects such as walls, furniture, and other objects in the indoor environments. The surface structure comprises a node for each surface and a link between any two surfaces can guide EM waves to each other. A reflecting surface can treat the EM wave propagation similar to the routing process in classic networking. Connecting two wireless devices becomes a problem of finding a route over reflecting surfaces, while blocking signals is achieved by absorbing or deflecting its EM emissions over certain frequency range. Using of the above configuration in RF, microwave and THz communication systems, which are severely limited in terms of very short distances and line-of-sight scenarios is of particular importance (Liaskos et al. 2017). The configuration can mitigate the acute path loss by enforcing the lens effect and any custom reflection angle per surface, avoiding the ambient dispersal of energy and non-line-of-sight effects, extending the effective communication range (Lee et al. 2012). In a simulated scenario, the functions can be applied to maximize the minimum EM received power over several receivers.

4. ELECTROMAGNETIC ENVIRONMENT

An EM environment is defined as a group of physical objects that considerably change the propagation of EM waves among various EM sources. In general, emitted EM fields undergo transmission, attenuation, and scattering before reaching an intended destination. In the environment there are various levels of EM fields at different frequencies where people are concerned about their possible health effects. One known case is EM hypersensitivity (EHS), which
occurs when the amount of EM fields surpasses the body’s power to deal with it where people complain of severe headaches, insomnia, heart palpitations and other acute EHS symptoms. Therefore, reducing EM field levels in buildings makes people with EHS comfortable.

4.1 Public Concern

Public concern over human effects of exposure to EM fields is largely based on a series of key epidemiological assessment studies. The results may only show an association with a stimulus since there are many factors involved with each person. In addition to epidemiological studies, a significant number of other studies have been carried out to date to explore the relationship between exposure to EM fields and various illnesses including EHS. These studies describe various experimental investigations with laboratory animals, tissue preparations, and cells, with detailed information on the bioeffects of EM fields (Habash 2007).

Concerning the EM health hazard concerns, there are three main uncertainties: (1) whether EM exposure poses a health hazard or not, (2) what components of the exposure contributes to the health effects (for example, time-weighted average or exposures above certain thresholds), (3) how serious the health effects are. Expert opinions regarding these three uncertainties vary widely. They range from a firm belief, based on physical reasoning, that EM exposure cannot possibly pose a health hazard to a conviction, based on epidemiological findings, that they pose a serious health hazard (Von Winterfeldt et al. 2004).

4.2 Exposure Limits and MF levels

Several decades of research in the area of bioelectromagnetics has led to a scientific consensus on the safety of EM fields. Expert committees reflect this consensus when developing safety standards and exposure guidelines. A safety standard specifies measurable field values that limit human exposure to levels below those deemed hazardous to human health (Erdreich and Klauenberg 2001). These standards consist of regulations, recommendations, and guidelines that would not endanger human health. The development of safety standards presuppose few procedures, including (1) systematic review of the scientific literature, (2) identification of the health hazards and risk assessment, and (3) selection of maximum permissible exposure (MPE) values that produce an environment free from hazard (Habash 2007).

People spend almost 90% of time inside buildings. For the above reason, a projection of EM emission levels from the existing and planned power distribution lines (13 kV area) around the building was developed. This projection is strongly connected to the well-being of the users where the health of building users should not be impaired by indoor EM conditions. Second, an analysis was conducted which included calculations for the planned bus ducts and major conduit runs as part of the system.

Since one of the objects of this study was in part to verify the levels of the ELF MFs around the building under consideration, a verification was made in regard to guidelines shown in Table 1 including the more restrictive Safety Code 6 (Habash et al. 2003; Safety Code 2009). MF intensities were measured on the proposed property using a milligauss (mG) meter to assess possible health risks and increase occupant comfort. The strength of the MF is expressed in units of Tesla (T) or microtesla (µT). Another unit, which is regularly used is the Gauss (G) or mG, where 1 G is equivalent to $10^{-4}$ T (or 1 mG = 0.1µT). The four measured zones of the building are shown in Figure 4. After assessing the area, it was determined that high MF level was measured in zone 1 due to the presence of power lines and transformers which border the zone. Projection of zones 2 and 3, which border St. Charles Street and Barrette Street, respectively, show that the MF levels range from 1 mG to 2 mG. This low level can be attributed to the fact that there are no power lines or transformers which directly border the property on these streets. The projected MF levels on zone 4 was a little bit higher than typical ambient or background MF levels found in buildings, which generally range from 0.5 to 3 mG.

1 $1 \mu T = 10$ mG
2 International Non-Ionizing Radiation Committee
3 Institute of Electrical and Electronic Engineers

4.3 Installation of Building Transformers
The installation of a new indoor power transformer substation, close to the buildings may be a very hard task with respect to the problems related to human exposure to ELF fields. This aspect is investigated to estimate the EFs and MFs from main power transformers. Each power transformer is to be placed in a switchyard near each building. A typical indoor power transformer substation has been considered in this study. The desired peak MF should be less than 10 mG at a distance of 10 m from the substation. The basic transformer ratings are: 3-phase, 100 kVA, 13.8 kV, 60 Hz. The transformer has input and output supply power cables, and outgoing distribution cables. The in and out current values have been chosen referring to nominal data of public distribution substations in Canada. Usually, the calculation of the MF is carried out in two parts, the field from the windings, and the field from the leads. Scaling down the EM calculated from 250 MVA using 3D finite element software Ansoft Maxwell, the peak values of the MF surrounding area of the proposed transformer are typically below the desired range of 10 mG. The influence of the transformer itself may be differentiated from the impacts of other sources of MF once the transformer is on site.

4.4 EM Mitigation

Much of the EM mitigation plan will be in the form of low-cost engineering modifications. For ELF fields, the first measure is to change the planned routing of a high-current bus duct that connects the utility transformer to the building distribution equipment, and importantly to avoid ceiling area routes. As a second mitigation measure, a special field shielding scheme may be incorporated into the new power facility construction sequence. This may include the installation of special MF shielding material below the large utility transformer and on portions of the walls and ceiling, plus in areas of the adjacent electrical distribution room, prior to the placement of switching equipment (ICNIRP 1998). Measures to reduce MF levels that may exist in a building during construction or as a result of building refurbishment or expansion are more efficient and cost-effective if implemented as an integral part of the design process. Although the total mitigation plan slightly increases the price of the building, however, it is a very small fraction of the total cost.

Mitigation and shielding of existing EM fields including MF and RF, represent a reasonable way to create healthier environment in the building. A scheme to implement EM mitigation measures during the design and construction of electrical and communication systems should be considered. Considerations should be given to use shielding techniques from the side of zone 1 (Figure 4), however sometimes protection from the impact of external sources can worsen environment as a result of internal sources impact. Other approaches include properly locating transformers, main electrical feeder lines, and switchboards into the building: use of wired systems or proper placement of wireless routing communication systems (Habash 2001). An arrangement called “reverse phasing” should be used with conductors so as to ensure a quick decrease in MF strengths with distance from the conductors. Finally, calculations of EM fields should always comply with the protection guidelines.

5. CONCLUSIONS

The objective of this study is to evaluate and optimize the energy performance, wireless connectivity, and EM environment in a mixed-use building. This information would be invaluable for a building owner to enable planning and prioritization of improvement activities. Creative architectural, engineering and computing, environment and health solutions that capitalize on the concept of “friendly buildings” have been presented. An HVAC zoning technique solution and optimized energy saving building materials are proposed. The use of emerging nanomaterials and metamaterials in construction as clearly connected to sustainability is discussed. A software-based control over the EM behavior of the wireless environment using metamaterials and metasurfaces, which may interact with imposing waves in PWNs, is presented. As a result of the above consideration, the design of the proposed building is healthier, energy-efficient and sustainable alternative to a traditionally built environment. Finally, it must be noted that the above proposed guidance advocates for the design

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of full EM frequency spectrum architecture, a design approach that takes into account not only the visible light portion of the spectrum but also ELF, RF, and THz portions.

Table (1). Exposure limits for uncontrolled ELF environments according to three protection guidelines

| Code        | Frequency        | Electric Field Strength (V/m) | Magnetic Field Strength μT |
|-------------|------------------|-------------------------------|----------------------------|
| Safety Code 6 | 0.0903-1 MHz    | 280                           | 2.73 µT                    |
| ICNIRP      | 50 and 60 Hz     | 5000 (50 Hz) 4200 (60 Hz)     | 100 µT (50 Hz) 83 µT (60 Hz) |
| IEEE' 2002  | 50 and 60 Hz     | 5000                          | 904 µT                     |

Figure 1. Architectural rendering of the building complex

Figure 2. HVAC simulation when a single zone is activated.

Figure 3. Wireless connectivity within and outside one unit of the building.

Figure 4. Aerial view of the proposed building complex divided into four zones for MF measurements.

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