



Printable and Flexible Electronics Enabled Intelligent Buildings: New Functions, Improved Performance and Optimized Control

A CABA WHITE PAPER

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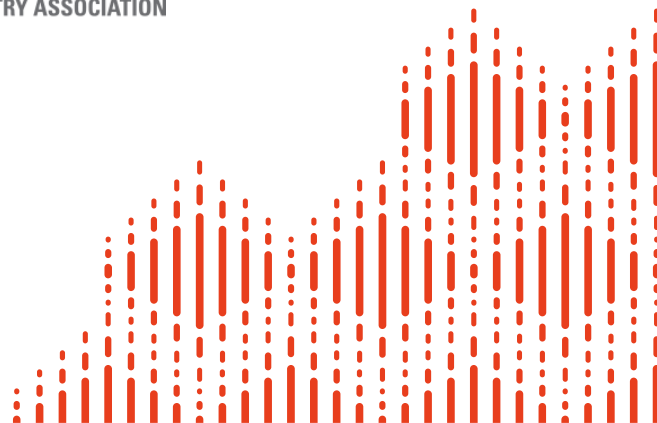
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ABOUT CABA

The Continental Automated Buildings Association (CABA) is an international not-for-profit industry association, founded in 1988, and dedicated to the advancement of intelligent home and intelligent building technologies. The organization is supported by an international membership of over 330 organizations involved in the design, manufacture, installation and retailing of products relating to “Internet of Things, M2M, home automation and intelligent buildings”. Public organizations, including utilities and government are also members. CABA's mandate includes providing its members with networking and market research opportunities. CABA also encourages the development of industry standards and protocols, and leads cross-industry initiatives. CABA's collaborative research scope evolved and expanded into the CABA Research Program, which is directed by the CABA Board of Directors. The CABA Research Program's scope includes white papers and multi-client market research in both the Intelligent Buildings and Connected Home sectors. www.caba.org.

ABOUT CABA'S INTELLIGENT & INTEGRATED BUILDINGS COUNCIL (IIBC)

The CABA Intelligent & Integrated Buildings Council works to strengthen the large building automation industry through innovative technology-driven research projects. The Council was established in 2001 by CABA to specifically review opportunities, take strategic action and monitor initiatives that relate to integrated systems and automation in the large building sector. The Council's projects promote the next generation of intelligent building technologies and incorporate a holistic approach that optimizes building performance and savings. www.caba.org/iibc.

About CPEIA

Established in 2014, the Canadian Printable Electronics Industry Association (CPEIA) brings together key Canadian and international players in industry, academia and government to build a strong Canadian printable, flexible and wearable electronics sector and ecosystem. The Association is the united voice for the sector and implements critical development strategies to facilitate growth through networking, stimulate R&D and investment, build a strong supply chain and drive the broad adoption of PE by end customers in a range of Canadian industries, including Intelligent Packaging, Intelligent Buildings, Aerospace and Defence, Automotive and Industrial Applications, Health and Wellness, Intelligent Documents, and Consumer Electronics and Wearables.

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EXECUTIVE SUMMARY

The advent of printable and flexible electronics (PE) can be hailed as being close to the pinnacle of the digital age, being a fusion of mass production, computer design, innovations in circuit board printing and microfabrication. There are many potential applications of printable and flexible electronics, from innovating consumer devices, to creating a fully sensed industrial operation. At the same time, energy spending in buildings is under scrutiny at the highest levels of corporations. Long-neglected deferred maintenance plans are being viewed as opportunities for savings, not liabilities.

The domain of commercial building applications, while well established, has the potential to be a rich application area for PE. This is due to two main factors. First, building technology is rapidly adopting fully digital controls and energy efficient applications. Second, the flexible and extensible nature of PE as a platform enables close to infinite customizability of the equipment and devices themselves.

Over the past 10 years, financial capital has become available to not only fund the deployment of advanced technology, but to give rise to new financial models that will spur innovation and deployment. Printable electronics are no different; there is potential capital and technological value, but where in the building ecosystem can it fit in? How can it help make buildings more energy efficient, better performing and of improved value to stakeholders?

This paper examines how this additive manufacturing technology, PE, can play a role to evolve the function and operation of commercial buildings. We focus on the major components of building automation systems, with two purposes: First, it explores how PE can change building operations and automation systems, enabling improved control, sensors and ultimately better conditions for those inside. Secondly, to assess the degree to which these technologies are ready for development and deployment.

This paper also explores some of the specific applications where this technology can provide disruptive and compelling alternatives to some of the conventional technologies used in the intelligent building industry. The focus of this report is the near-term, just-on-the-horizon technology applications that can be developed into fully commercial offerings within the next few years. For the applications of PE in the intelligent building ecosystem, the authors attempted to discern “science fact” from “science fiction,” in terms of what can be done to deliver clear value.

1. INTRODUCTION

The modern commercial building is morphing into an intelligent building at a rapid pace. Sensors, analytics, and controls will improve efficiency, services, occupant comfort and safety. Navigant Research forecasts that building automation system (BAS) revenues will grow from \$58 billion US in 2013 to \$91.9 billion US in 2023, globally. This relatively modest growth does not capture the additional value that advanced sensors and controls, enabled with new technologies such as printable and flexible electronics, will bring to commercial office space.

The increase in value from advanced sensors and controls is due to a number of overlapping factors, such as: **materials, communication, capital, codes and standards, and people.**

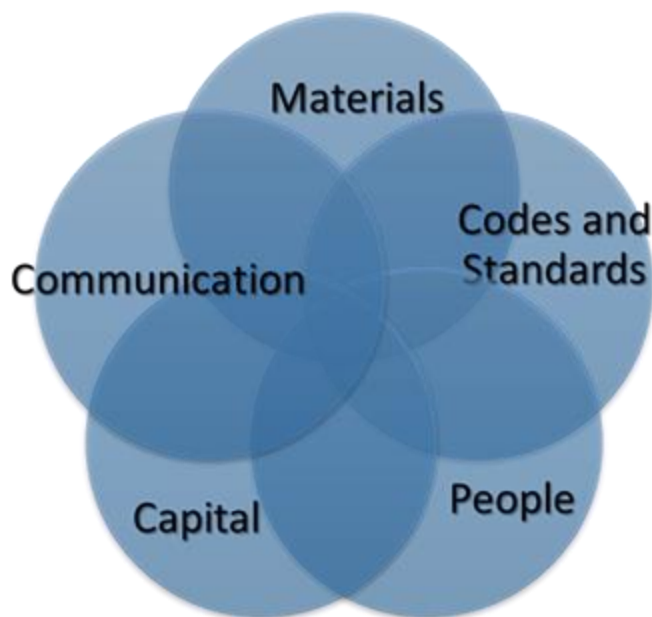


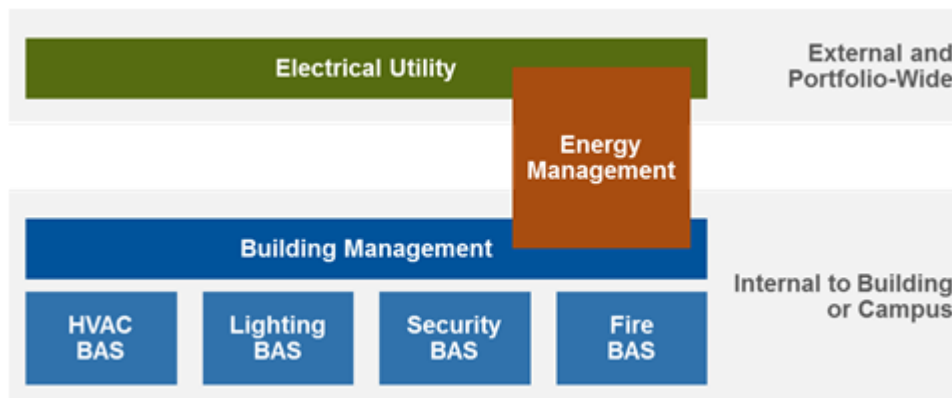
Figure 1 Factors that accelerate adoption in intelligent buildings

- **Materials:** Innovative materials are enabling new products for the BAS market. These materials include smaller and cheaper computer chips and sensors, advanced components like smart glass, and innovative manufacturing processes, like printable and flexible electronics – the subject of this paper.
- **Communication:** Communication interconnects sensors and controls systems. Wireless technology is now a standard form of communication, and novel methods of network communications, like Power over Ethernet or fiber optics-based communication, are being deployed in pilot programs globally. In addition, technology companies are consolidating the many communication and control standards that exist, with the prospect of simple and easy device communication in the future.
- **Capital:** Over the past 10 years, financial capital has become available not only to fund the deployment of advanced technology, but to create new financial models that will

spur innovation and deployment. Energy spending in buildings is now under scrutiny at the highest levels of corporations. Long-neglected deferred maintenance plans are being viewed as opportunities for savings, not liabilities.

- **Codes and Standards:** In addition, the service model of technology deployment is slowly gaining traction in commercial buildings. This leads to contracts based on payments for building services (e.g. for lumens, for chilled air, heat, etc.). Building codes and standards are becoming viewed as tools to enact energy and carbon reductions. These tools evolve over the course of decades, but enable major changes in building technology.
- **People:** People are the most expensive and important asset in a commercial building. The increased ability to control the building environment and advanced building features provides improved comfort, health and productivity, and permits optimization of the personalized work environment.

This paper examines how one new additive manufacturing technology: printable and flexible electronics (PE), can play a role in the evolution of the function and operation of commercial buildings. We focus on the major components of building automation systems, as presented in the figure below: **lighting; heating, ventilation and air conditioning (HVAC); fire; and safety.** Each of these four building automation systems provides a different service and value to commercial tenants and operators. In the greater context, these four systems rely on power from a public utility (or local renewables). Better control of building automation systems leads to more efficient operations, lower maintenance costs, and reduced expenditures for energy.



(Source: Navigant Research)

Figure 2 Building Automation Systems (BAS) in the context of energy and control

In each of the following sections, the authors explain how printable and flexible electronics could change the value, operations, and services of each BAS subsystem. In addition, the authors present a grading of each application in terms of the Technology Readiness Level

(TRL), a method for assessing the maturity of a technology¹. According to the National Aeronautics and Space Administration (NASA), the TRL Levels are defined as such:

TRL 1	Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.
TRL 2	Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of concept: Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.
TRL 4	Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.
TRL 5	System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.
TRL 6	System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.
TRL 7	System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.
TRL 8	Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space): End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

¹ <https://www.nasa.gov/content/technology-readiness-level/>

TRL 9	Actual system "mission proven" through successful mission operations (ground or space): Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.
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(Source: NASA)

Table 1 TRL level definitions

The focus of this paper is on building features and technologies that are close to commercialization. It is beyond the scope of this paper to identify all applications. Instead, we provide a few applications the authors consider valuable for the intelligent buildings sector and the printable and flexible electronics industry to pursue in partnership.

2. WHAT ARE PRINTABLE AND FLEXIBLE ELECTRONICS?

2.1. System components and their applications

With PE, inks that can conduct electricity – made from materials such as graphite, silver, and copper – are printed on a substrate at high enough density to form a complete electronic circuit, but thin enough to have negligible impact on the substrate thickness. The substrate can be rigid, flexible or even stretchable, such as paper, plastic, fabric or glass. These inks can be applied through traditional printing processes such as flexo, screen, inkjet, gravure, and offset, as well as through coatings. This can be done through fast and inexpensive automated processes, such as those used in the commercial printing industry for newspapers and magazines. These electronic components can also be embedded through additive manufacturing processes, such as 3D printing or in-mold electronics.

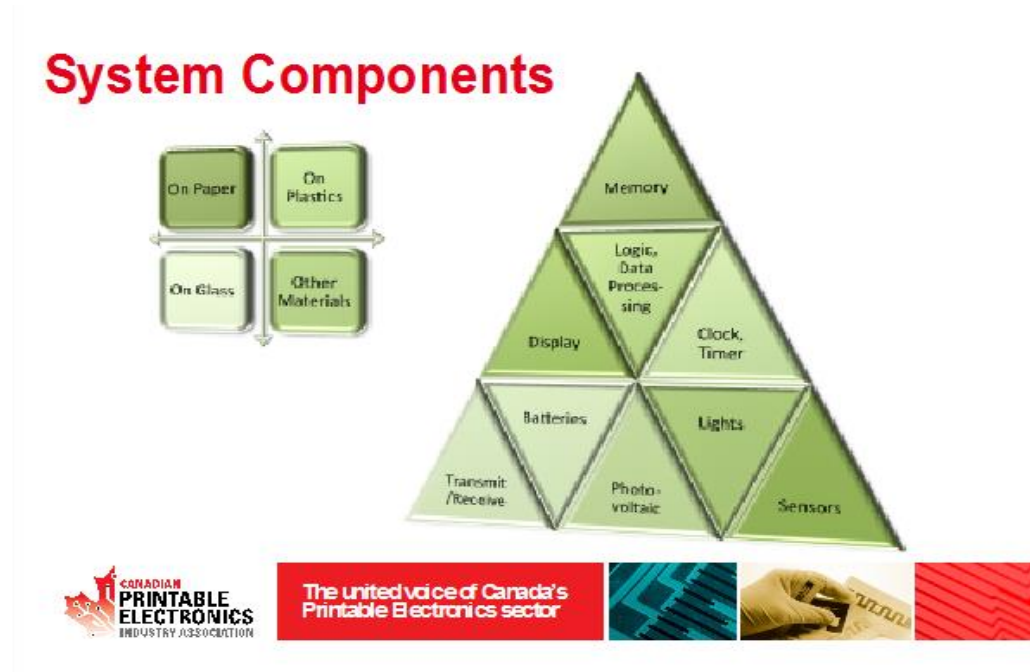


Figure 3 PE System Components

PE can be used to create discrete components such as displays, conductors, transistors, sensors, light emitting diodes, photovoltaic energy capture cells, memory, logic processing, system clocks, antennas, batteries, and low-voltage electronic interconnects. These can be integrated into simple systems that, for example, can record, store, and then transmit temperature information. Fully functional electronic systems can be created in this way, or discrete components and sub-systems can be produced to function as part of a hybrid solution with conventional silicon-based integrated circuits or components.

So Why Printable Electronics?



- 2D - easy to add a new function on the surface of buildings, equipment
- No power, low power, self-powering functions (e.g. passive sensors)
- Large surface and volume manufacturing
- Low cost (materials, production, R&D)
- Flexible, stretchable solutions
- Wide range of functions – sensors, displays, memory, antennas, lights...



Figure 4 Reasons for PE

PE can overcome the bottlenecks around the issues of cost, manufacturing complexity, and even environmentally sound disposal and recycling, to:

- Add intelligence to everyday objects, as envisioned by the Internet of Things (IoT), by creating functional electronics in the form of labels that can be added to just about anything for tracking or communication.
- Embed electronic functions within interior design elements such as cubicle walls and ceiling panels, reducing, if not eliminating, the need to run traditional cabling.
- Dramatically reduce the form factor of three-dimensional, traditional electronic systems, sub-systems, and devices with hybrid solutions by replacing traditional components with two-dimensional printed alternatives.
- Open up a whole new world of large-area flat and flexible displays – electronics that can be added to base structures within or outside of buildings
- Be used to create energy-harvesting systems, such as photovoltaic windows/blinds, and/or create low-power systems that can operate as self-powered with harvested energy.

PE technology has been under development for 10 to 15 years in various parts of the world. Large volume commercial applications are now being marketed in:

1. Consumer products such as organic electronic TVs, monochromic book readers.
2. The automotive sector through control panels, antennas.
3. Intelligent packaging through labels that measure food freshness.
4. Security documents that embed electronic features.
5. Health and fitness applications where it can measure heart rate, body temperature, embedded into wearable devices.

This technology has a number of real and potential applications for intelligent buildings.

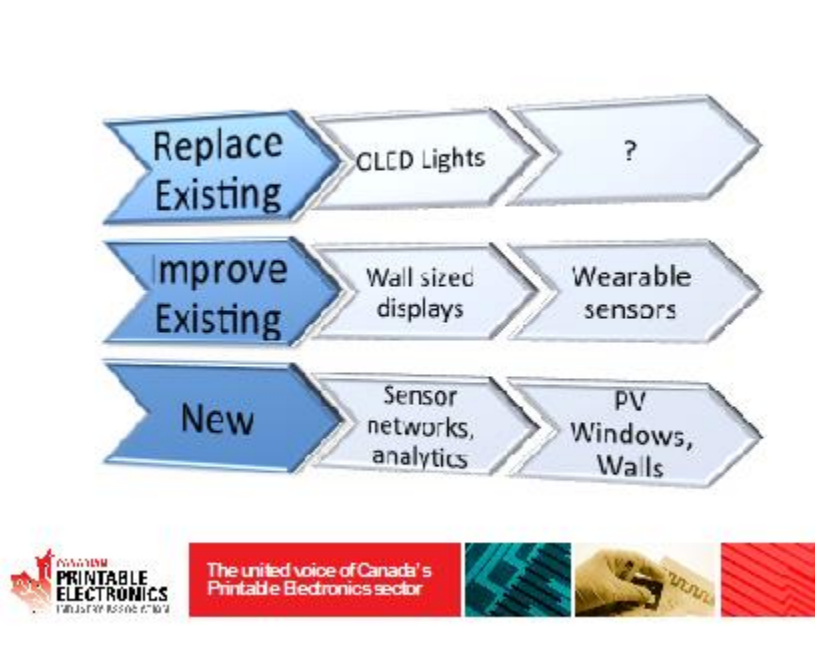


Figure 5 How PE can be used in intelligent buildings

2.2. An A/B example: The typical office ... remade

A typical office space has both ambient lighting and task lighting. The ambient and task lighting may be adjusted by the office occupant to meet specific needs. The office also includes a daylight-harvesting light sensor that reduces the intensity of artificial light in response to natural light, and an occupancy sensor that shuts the lights off when no one is present, and a thermostat. In addition, there is a smoke/fire detector and an alarm annunciator to provide indication of a fire. Traditionally, each of these is a discrete component, hardwired to a controller that provides localized control, as well as to a building-wide system for global control (for example, to set minimum and maximum allowable temperatures, to turn off the lights at night, and for the safety and security system). It requires a relatively large amount of labor to install and wire all of the separate components. Further work is required for commissioning – that is, to provide an association between the electrical wiring and the physical layout.

When the same office space uses PE components and sub-systems there are various advantages, such as:

- The ambient lighting is replaced with a thin sheet of light (using either organic LEDs or an array of inorganic LEDs). This sheet also includes a printed daylight-harvesting sensor, a printed occupancy sensor, and a printed temperature sensor.
- The local controls for providing daylight harvesting and occupancy control are printed on the sheet of light. This simplifies installation and wiring, and greatly reduces the local control burden on the central control system.
- The printed temperature sensor is tied into the heating, ventilation and cooling system and also can provide information to the safety system. The lighting is tied into the safety system and is programmed to change color and provide directional exit information in case of fire.
- Since the functional electronics for all these applications are printed, installation is simplified and costs are reduced. A further advantage is that the printed components are much thinner than conventional components. This allows for more usable space to be created within the building.

How close to market is an integrated system such as this today? Flexible sheet lighting technology is already on the market. The sensors and other discreet PE components are in various phases of development. More work must be done, not just in technology development, but also in certification to meet building code requirements.

The following sections explore some of the specific applications where this kind of technology can provide disruptive and compelling alternatives to some of the conventional technologies being used in the intelligent building industry. Our focus is on technology applications that can be developed into fully commercial offerings within the next few years.

3. LIGHTING AND LIGHTING CONTROLS

3.1. An overview of lighting in buildings

Great improvements have been made in reducing the energy consumed by lighting. About 25–30% of all generated electricity is used for lighting. Improved lighting efficiency can produce large reductions in energy consumption and reduced generation of greenhouse gases. The efficiency of producing visible light, a lighting system's "luminous efficacy," is measured in lumens/watt (lm/W). Solid state lighting sources, such as light emitting diodes (LED), have set the new standard for luminous efficacy. But we can do more to reduce energy usage than just increasing the lm/W of these lighting sources.

The United States Department of Energy (DoE) estimates that about 143 trillion btu of energy has been saved by implementing solid state lighting and that ultimate savings could reach almost 5,000 trillion btu of energy.² Standard general service incandescent lamps typically have a luminous efficacy in the range of about 10–20 lm/W.³ Energy saving mandates in

² United States Department of Energy publication DOE Solid State Lighting Program, Modest Investments, Extraordinary Impacts, September 2015.

³ United States Energy Independence and Security Act of 2007 (EISA 2007).

many countries have effectively eliminated many of these lamps by putting minimum luminous efficacy requirements on all lamps, independent of light-emission technology. Today, inorganic LED lamps and luminaires are available with luminous efficacies over 100 lm/W. Individual inorganic LEDs are commercially available having efficacies of 180 lm/W and over 300 lm/W in research demonstrations.

As can be seen from these numbers, while energy efficiency still matters, LED-based lighting is available that can cut costs by over four times that of incandescent lighting. Even greater energy savings can be enabled with controls that dim or turn off lights when not required. A very common example of lighting controls is occupancy sensing that turns off lights when a room or space is not occupied. In some cases, the lights, or a portion of the lights, are dimmed to provide a safe level of ambient lighting. Additional savings can be achieved by using daylight harvesting – that is combining the use of natural and artificial light, with controls that modify the intensity of the artificial light in response to the available natural light, to achieve a desired light level. Both of these controls are commercially available and are an integral part of energy savings using solid state lighting.

3.2. The evolution of lighting

There are two main types of light sources for solid state lighting: inorganic LEDs and organic LEDs (OLEDs). Inorganic LEDs are point sources, while OLEDs naturally emit light over large areas. At this time, inorganic LEDs have higher efficacy, lower cost, and a longer lifetime. LEDs are the light sources used in almost all commercially available solid state lighting, but OLED performance continues to increase. The unique ability of OLEDs to produce comfortable, uniform, non-glare light in a large area, in a very thin and potentially flexible form factor, offers unique opportunities for solid state lighting in general and specifically for PE.

3.3. Productivity and wellness

An intelligent building, however, goes beyond straightforward energy savings and solid state lighting. Coupled with the interconnectedness inherent in an intelligent building, there are a number of other attributes that make possible impacts even more significant than energy savings, namely in productivity and wellness. Solid state lighting has two key attributes that are necessary to address productivity and wellness:

1. **The ability to tune the color:** Color tuning is important because the color of the light in which we live can affect our productivity, our mood, and our health. There are numerous studies showing the benefit of changing the color of light throughout the day or for different tasks. Our evolutionary history of living outdoors has conditioned us for relatively cooler white (more blue) in the morning and a relatively warmer white (more red) in the evening. Such color shifts are well demonstrated to affect Circadian rhythm. They can be used to boost productivity, reduce fatigue (e.g., in shift workers and people performing critical tasks such as air traffic controllers), and aid in the treatment of various health issues such as attention deficit disorder and dementia. A means to easily control the color and intensity of light is necessary to realize these benefits.

2. **The ability to be interfaced easily to the control system of an intelligent building:** Solid state lighting, including both OLEDs and inorganic LEDs, permits control of color, or spectral power density. In both types of LEDs, the spectral power density of a device can be varied over a relatively wide range at the time of manufacture. In use, color tuning is typically achieved by varying the intensity of two or more devices, each having a different color, or spectral power distribution. The fact that LEDs are DC-powered components makes control of the intensity relatively easy.

3.4. OLEDs and printing lighting

OLEDs offer a unique opportunity to incorporate lighting and printable electronics in the intelligent building. OLEDs are manufactured using a printing process similar to that used to manufacture other PE components. They can be fabricated in rigid and flexible forms. OLEDs are very thin, and thus, can be easily integrated into walls and ceilings. Thin form factors reduce the space in non-occupied spaces, potentially permitting an increase in the ratio of occupied to non-occupied space.

There is significant cross-over between the processes and materials being developed for PE and OLEDs, including substrate materials, printing technologies, electronic packaging approaches, and equipment. As shown in the A/B example (section 2.2) with the office remade, this offers the potential for the direct integration of OLED lighting with sensing, communication and control functionality.

OLEDs can be printed in semi-transparent form, leading to the possibility of intelligent skylights and windows. While electrically dimming glass exists today, (for example, using an electrochromic coating), an OLED intelligent window or skylight could provide natural light when available, or artificial light when natural light is not available.

3.5. Printing advanced lighting control

The ability to incorporate different functional components in printed fashion on one substrate offers other possible enhancements to an intelligent window or skylight, such as:

- First, the OLED could consist of two or more OLEDs having different colors – for example, a warm white and a cool white. These could be individually controlled to provide a specific color of light in the room. In one example, a printed color sensor could be integrated with the OLED that is used to match the color of the artificial light to that of the natural light. This multi-color capability could also be used to provide a light color and intensity specific to the application and time of day.
- In another example, a transparent photovoltaic cell could be printed on the substrate to provide power for the daylight harvesting system. While such transparent photovoltaic systems have relatively low efficiency, they may be able to provide enough power for the occupancy or daylight-harvesting systems, or for a wireless control node to interface the window to the building control system.
- Lighting is personal – different people have different lighting preferences. Part of an intelligent building is moving from the one-size-fits-all approach of current lighting systems to personalized lighting.
- PE enables low-cost sensors or sensor networks that can be incorporated into lighting, or into the building architecture, to identify spaces or people and adjust the light environment accordingly. In different situations, such control may include the

light intensity level, the color temperature and the light distribution pattern. Such systems may offer different modes of control such as manual control by occupants from a smart phone, or by using pre-programmed lighting schemes as a function of time and location.

- The ability of PE to produce large numbers of low-cost devices and sensors that can be used separately or integrated with other PE components permits a higher degree of granularity in the control of lighting systems. This produces a more individualized environment with increased comfort and satisfaction.

3.6. Visible light communication

Another aspect of networked light is the ability to use the light source as a communication pathway. Visible light communication, or LiFi, can permit one or two-way communication and localization capabilities by low-level modulation of the intensity of the light used for illumination, at a frequency well above the visual threshold. Such a system could be used to broadcast information to general public receivers, such as cell phones, or keyed to particular receivers or to a location. Various methods may be used for localization, including combinations of occupancy sensors, pressure-sensing mats, video sensors, thermal sensors, light-based communication, and others. In summary, there is a need for a large array of inexpensive sensors, preferably more than one type to improve sensing accuracy and to provide the required level of granularity. PE is uniquely suited to provide a wide range of low-cost, interconnected sensors and the ability to integrate these with light-emitting elements.

3.7. The value of printing lighting

PE can also be used to enhance operations and maintenance by collecting information such as light or sensor failures, run hours, voltages, amps, ballast health, and battery life. Providing additional data from the lighting devices by using low-cost PE devices or accessories can allow staff to monitor equipment life and operation and track fault detection and diagnostics, which can be used to monitor the lighting systems proactively and extend operational life of building systems.

Table 1 shows a tabulation of the technical readiness level of some of these PE-based solutions. While there are a number of commercially available OLED-based luminaires, Table 1 includes a category for large area, high efficacy OLED lighting for general illumination, which is not yet commercially available.

PE-enabled solution	TRL	Potential Market (e.g., units/building)	Tech readiness development challenges	Drivers for adoption	End-user wants, needs	Next steps for market ready product (time to market)
Large area, high efficacy OLED lighting for general illumination	3	General illumination in buildings	Improve efficacy Improve yield on large areas Reduce cost Increase lifetime	Provide high quality comfortable light Minimize space and volume taken up by lighting system	Comfortable personalized light	5+ years

Color tunable OLED	3	General illumination in buildings providing enhanced user experience	Integration and control of multi-color emission All challenges for OLED in general	Color tunability	Comfortable personalized light	7+ years
Visible light communication	7-8	In buildings	Cost Acceptance Standards	Increased information and interaction with customer Improved experience for user	The information that they want in a timely fashion, no extraneous information	Commercially available now
Sensors and Electronics	4	General illumination in buildings providing enhanced user experience	Performance and functionality Reliability Cost	Improved control Increased granularity of control	Personalized lighting experience	1-2 years
PE photovoltaics and energy harvesting	4	General illumination in buildings providing enhanced user experience	Performance and functionality Reliability Cost	Improved control Increased granularity of control	Personalized lighting experience	1-2 years
Fully integrated lighting/sensor/control network based on PE and large area OLED illumination	2	General illumination in buildings providing enhanced user experience	All of the above	Increased information and interaction with customer Improved experience for user Increased granularity of control Improved control	Personalized lighting experience The information that they want in a timely fashion, no extraneous information	10 years

Table 2 Printable electronics and lighting TRL

4. HEATING, VENTILATION AND AIR CONDITIONING SYSTEMS

4.1 More data, more control

Heating, ventilating and air conditioning (commonly referred to as HVAC) systems are designed to provide thermal comfort for building occupants. These systems are designed to provide a comfortable environment while minimizing energy usage and maximizing overall effectiveness.

As can be seen in figure below, HVAC control systems consist of the following components:

- **Sensors**, including temperature, airflow, humidity, and occupancy. These sensors account for the vast majority of all sensors used in advanced HVAC control systems.
- **Field devices**, which includes controllers that regulate terminal units. These devices include thermostats, variable air volume (VAV) controllers, and Fan Coil Unit (FCU) controllers.

- **Floor-level controllers including air handling unit (AHU) controllers**, which typically manage distribution of air through VAV systems as well as supervisory-level system controllers.
- **Building-level controllers** manage the primary conversion of energy, including chillers, boilers and packaged unit controllers etc.

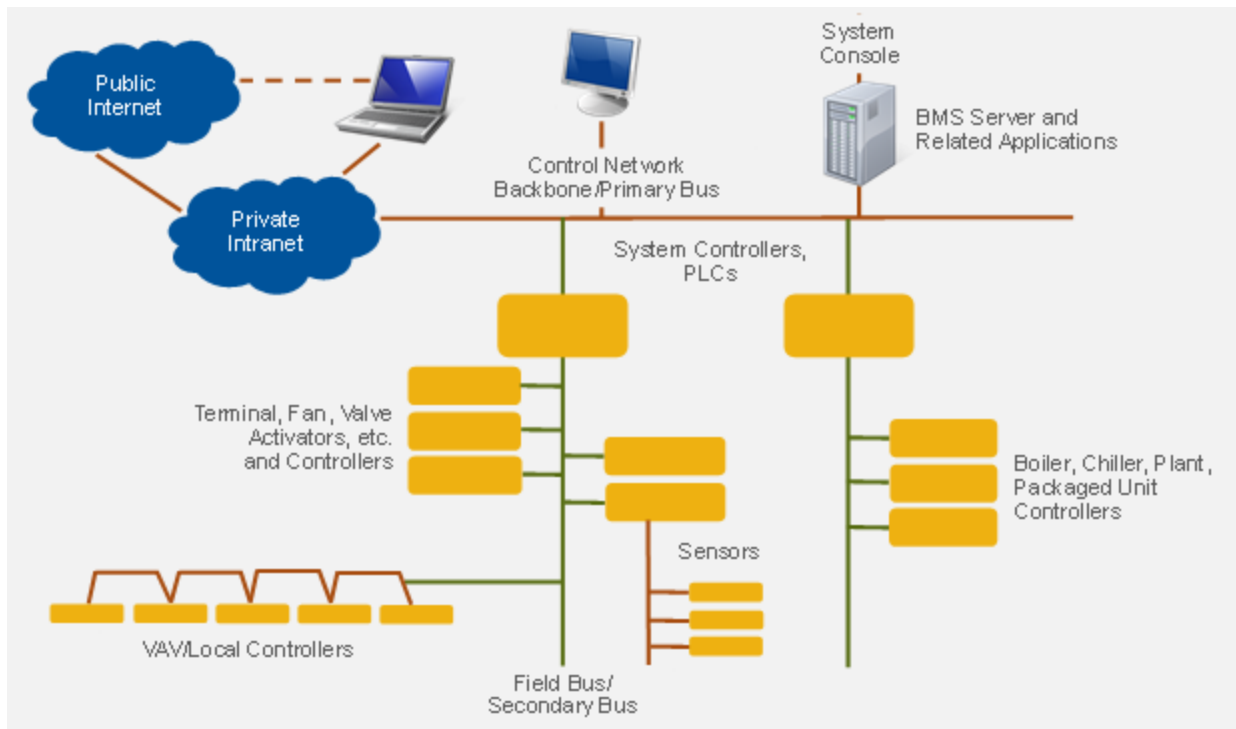


Figure 6 Building Automation System Components

With printed circuits, low-cost, low-powered sensors and controllable devices can be created for HVAC applications, which enable more points to be monitored, and additional data to be collected. These additional points and data provide enhanced control and improved information about operation, airflow and temperature that once required significant hardware expenditures, disruption to operations and potential add-on projects.

4.2. Building size no longer an issue

Historically, HVAC building automation systems have been too complex and too expensive for smaller buildings to install, leading to building operations that fall short of its full potential. These small buildings represent an opportunity to lever low-cost, wireless PE sensors and devices to increase energy efficiency and operational data monitoring.

Among the largest contributors to energy expenditures in commercial buildings, HVAC systems are also typically oversized in order to meet comfort demands on the hottest and coldest days of the year. HVAC controls represent a critical part of building energy management, as they are often the single biggest users of building energy, accounting for over 40 percent of the typical building energy use profile.

The total cost of adding sensors to an HVAC system includes the cost of the device hardware, distribution wiring and the cost of installation. As explained in section 2 of this paper, printed sensors and devices can reduce both of these costs because they are a cheap, additive technology. Additionally, using wireless communications with PE in HVAC applications reduces the installation labor required compared to conventional building automation systems.

4.3. Benefits of low-cost printed sensors

Shifting to low-cost printed sensors using wireless communication also enables more sophisticated control. HVAC systems at a minimum regulate the temperature of the air in a building. Sensor and integration costs prevent many systems from providing any additional functionality, though control of humidity, carbon dioxide, and airborne contaminants can be achieved. Once a PE-based control system has been installed, the incremental cost of adding new sensors will be much lower than that of adding devices to a conventional system that are inherently more expensive, bulky, and may have to be hardwired. As a result, more sensors can easily be added to provide more granular control and data for the HVAC system.

However, PE technology still faces the technological challenges of receiving adequate power and communicating robustly. The distance between a sensor and controller can exceed the maximum communication distance of a wireless device, particularly if it is run with ultra-low power. Additionally, the structural building elements in the ceiling interfere with radio frequency (RF) communications. These issues could be overcome by using a mesh network approach with multiple nodes on a network to rebroadcast the signal.

On the plus side, some of these sensors can be self-powered through photovoltaic and local batteries, all of which can have a printable electronics component. Should direct wiring be required, wiring can become a design element, like a wallpaper strip, eliminating the need to open walls. As a result, each application and installation should be evaluated for communications and power options to ensure that appropriate protocols or approaches are used, as some options can be more expensive.

Added benefits for productivity, comfort PE can also be used to enhance productivity and comfort in communal and meeting areas. For example, in an intelligent building, a meeting room has a schedule that includes the number of attendees for each meeting. On average, a person radiates about 100 watts of heat per day, so a large number of occupants can materially affect the temperature in a room. In an intelligent building, the building control system could pre-adjust the temperature of the room based on the expected occupancy to achieve the desired temperature, resulting in a more comfortable and productive meeting. In addition, quantitative occupancy sensors could determine if the expected number of occupants actually showed up and, along with temperature sensors, be used to adjust the temperature accordingly. While this could be done just with temperature sensors, such a system is reactive in that it has to wait for the temperature to change, whereas a system having multiple sensor inputs can provide proactive temperature regulation.

4.4. Equipment-level control

In addition to enabling better system-level control through better collection of building data, PE sensors can provide equipment-level control as well. There is potential for great cost savings from the use of advanced HVAC controls to eliminate standard preventative maintenance of equipment through the use of automatic fault detection and diagnostics (FDD). HVAC equipment generally fails from prolonged periods of use or from use when the motor temperature exceeds its design threshold. By monitoring gradual temperature changes and acting at exactly the right time, failures can be dramatically reduced and equipment will run at peak efficiency. PE sensors that connect directly to equipment to monitor conditions can provide the kind of information needed to identify problems before they affect building operations.

- **Potential market (e.g., units required per building).** Navigant Research expects nearly 23.7 million networked HVAC sensors for commercial buildings to be shipped globally in 2015. PE HVAC sensors not only have the potential to capture that market, but can also expand the market by lowering the cost of HVAC controls, thus, enabling more sophisticated systems with a greater number of sensors.
- **Technological readiness/Development challenges.** The technology gaps that remain for PE HVAC sensors are ensuring that sensing and wireless communication can be accomplished with ultra-low power. Actually supplying power to devices could be accomplished by converting ambient solar, thermal, or kinetic energy to electrical energy.
- **Drivers for adoption.** Decisions to adopt advanced HVAC controls are driven largely by the overall value proposition or return on investment (ROI) they provide, typically accounting for reduced maintenance costs, reduced energy costs, and increased equipment life-span. Using PE devices in these applications can improve the ROI either by reducing the cost or increasing the benefit by providing more sophisticated control.
- **End-user wants/needs.** Ultimately end-users want a building that can maintain a comfortable environment. Once that is achieved, end-users want to maintain that level of comfort as efficiently as possible. Designing buildings with more control points and richer data enables more robust building analytics to achieve occupant comfort and energy efficiency.
- **Next steps to achieve a market-ready product.** Once technological challenges are tackled, building automation system architecture must be adjusted to allow for more data inputs. This will create integration challenges and require more sophisticated algorithms.

PE-enabled solution	TRL Level	Potential Market (e.g., units/building)	Tech readiness development challenges	Drivers for adoption	End user wants, needs	Next steps for market ready product (time to market)
PE temperature sensing element	4	There is at least one temperature sensor per zone in a building. Navigant Research estimates a global market in excess of 10 million units annually.		Provide more inputs for better thermal control and reduced energy costs	Thermal comfort	1-2 Years

PE occupancy sensing element	4	About two million HVAC occupancy sensors are shipped annually	Adaptation of PIR occupancy sensing technology to PE sensors	More efficient operation of HVAC equipment	Reduced energy consumption	1-2 Years
PE wireless communication for sensors	4	By 2020, wireless controls are expected to account for about 5% of networked controls	Power consumption	Lower installation cost of control systems	Flexibility	1-2 Years
PE Energy harvesting	4	Every wireless sensor could benefit from energy harvesting	Functionality, reliability, cost	Lower installation costs through the elimination of power wiring	Truly wireless control networks	1-2 Years
Photovoltaics on external building envelop	4	Surface of buildings can be utilized	At demonstration stage, integration with or addition to existing surfaces	Low cost through PE to generate renewable energy Retrofit capable	Reduced energy costs, renewable energy, green buildings	3-4 years

Table 3 Printable electronics and HVAC TRL

5. FIRE PREVENTION AND PROTECTION SYSTEMS

5.1. Overview of fire systems

Fire protection in buildings depends on active fire protection, passive protection, and fire prevention.

- **Active fire protection:** is the use of manual or automatic systems designed to detect, control, and extinguish fires within buildings.
- **Passive fire protection:** relies on the design of the building to limit damage and provide more time to evacuate by compartmentalizing fire through the use of fire resistant material.
- **Fire prevention:** is the process of minimizing ignition sources and educating building occupants on fire safety.

By reducing the cost of fire sensors, PE can serve an important role in expanding both active fire prevention and fire protection.

5.1.1. Active fire prevention systems

Active fire prevention systems are composed of smoke, heat and carbon monoxide sensors; fire door and fire/smoke damper controllers and actuators; voice evacuation, public address systems and alarms; emergency egress lighting controls; and master fire alarm control panels. Local, state, and national codes for fire and life safety controls determine the minimum requirements for these systems and vary depending on building type and facility use. Insurance requirements also have an influence on minimum system requirements. In

addition, building owners may have their own special requirements for the fire safety system. Most active fire prevention systems installed, though, are designed to only provide what is required. But the primary barrier to installing more complex active fire prevention systems is substantial added cost with little added benefit.

5.1.2. Fire protection systems

Fire protection systems are designed to operate in emergency conditions and necessitate redundancy and robust design. Reliability is the primary concern of such life-critical systems. Additional sensors (e.g., occupancy sensors) may be deployed to complement existing fire and life safety systems and provide a secondary level of knowledge during a fire or life safety event. For example, occupancy sensor data can alert security professionals to the presence of people in lavatories or closets during an emergency such as a fire.

5.2. Printable electronics and fire

PE could reduce the cost of these additional sensors to the point that their benefits outweigh their costs. As with any component of a fire prevention system, however, the operation of PE fire devices must be proven in extreme fire conditions.

Outside of active fire protection systems, PE can play a role in fire prevention.

PE could enable the cost-effective deployment of a ubiquitous sensor network that can monitor for fire hazards such as gas leaks or other flammable materials.

When a fire crew arrives, it is imperative to receive an up-to-date picture of where occupants are within the building. By adding smart sensing features to the building and to occupant ID cards, an almost real-time view can be enabled by PE. More robust security and access controls enabled by PE (discussed elsewhere in the paper) can help serve as fire prevention tools by reducing the opportunity to start intentional building fires. Moreover, according to the National Fire Prevention Association (NFPA), the leading cause of fire that accounts for the most property damage in commercial office buildings is arson.

- **Potential market (e.g., units required per building).** PE sensors can provide an additional layer of information beyond active fire protection systems. Building codes require fire and life safety control systems in nearly every building globally. But the acceptability of new technology by these codes lags the development of new technology to ensure that systems remain robust and reliable.
- **Technological readiness/Development challenges.** As with all life-critical systems, reliability in extreme events is needed. PE technology needs to be developed to the point where it will have a high tolerance to withstand extreme conditions during a fire. On the other hand, PE components are less costly – more sensors can be added to create a mesh network that is not vulnerable to one even several points of failure.
- **Drivers for adoption.** Adoption of fire control systems is largely driven by building codes. The systems installed are designed to be the most cost-effective legally compliant systems. Because of the need for robust system design and components that function in fire conditions, the cost of adding new devices is typically larger than the benefit gained from a more complex system. But, due to low cost points, PE could reduce the expense of a retrofit.

- **End-user wants/needs.** The ultimate goal of fire and life safety systems is to minimize any loss of life during a fire, as well as minimize the impact to surrounding areas. It is important to note that while fire codes are designed for these objectives, they are not designed to protect the assets or operations within a building. As a result, there is a need for more advanced systems to provide better protection for building assets and operations as long as the total cost of the system is low.
- **Next steps to achieve a market-ready product.** The next step to achieve a market-ready product is to develop and test code-compliant PE devices.

PE-enabled solution	TRL Level	Potential Market (e.g., units/building)	Tech readiness - development challenges	Drivers for adoption	End-user wants, needs	Next steps for market ready product (time to market)
Secondary fire sensors	3	Fire and life safety control products account for just shy of \$6 billion globally	Assuring robust operation in fire conditions	Minimize impact of fires	Provide better protection for building assets and operations	5+ yrs
Occupancy sensors	4		Assuring robust operation in fire conditions	Minimize loss of life during a fire	Provide better protection of building occupants	1-2 yrs
Flammable chemical detection	3		Assuring robust operation in fire conditions	Minimize occurrences of fire events	Reduce fire risk	1-2 yrs

Table 4 Printable electronics and fire safety TRL

6. SECURITY AND ACCESS

6.1. A multi-faceted challenge

Building security encompasses considerations of a physical nature as well as virtual, digital or communications nature. Every building type necessitates its own security and access system. The type of building, for example, will dictate the level of security appropriate for it: a 30-storey tower will differ from a low-rise building. There may be a concierge on the premises 24/7 or it can be remotely monitored. In a multi-unit residential building, for example, there are numerous different areas on the premises to monitor, besides the residential quarters.

Access to, and safety of, service areas such as garages and staff entrance/side door/delivery areas should also be considered. In addition, accessibility for people with hearing, vision or mobility impairments is a major requirement, prompted by the market demand and supported by regulation.

Finally, concerns about theft and precursors of theft, terrorism (which can include tampering and poison), as well as cybercrime, emphasize the need for security management in an intelligent building. These factors establish security and access as a critical service where innovative efficient solutions will find a ready market.

6.2. Areas for consideration

What follows are examples of areas in buildings that may have physical or virtual vulnerabilities:

- Main reception
- Standard offices
- Computer server rooms
- Equipment facility rooms
- Valued assets locations (e.g., locations housing financial books, cash, art, etc.)
- Evacuation zones
- Elevator communications
- Entrance and gates
- Staff entrance/side doors
- Open air parking lots
- Storage
- Outdoor plazas

Each of these areas has specific security and access needs.

6.3. The role of Printable Electronics in Security and Access

While there may be multiple ways to address security concerns, the fundamental activities can be narrowed down to the following three:

- Detection of a vulnerability
- Communication of a vulnerability
- Remediation of a vulnerability

All three activities lend themselves well to solutions afforded by PE. These include ambient data collection through sensors, seamless authentication through application of biometric data, ubiquitous monitors, flexible lighting and power, mass communication systems, seamless integration into building design, electronic signage in full color, and accessibility solutions capable of identifying and responding to a need.

More specifically, the following PE-enabled solutions can be considered for security applications in intelligent buildings:

PE-enabled solution	TRL level	Potential Market (e.g., units/building)	Tech readiness - development challenges	Drivers for adoption	End-user wants, needs	Next steps for market ready product (time to market)
Sensors	7	\$9.2 billion RFID business consists mainly of passive RFID with disposable dumb tags, very price critical (~\$.08). \$8B fully printed sensors by 2015 (IDTechEx) (IDTechEx)	Cost, size are critical	24/7 ubiquitous monitoring, tracking of activities	Seamless access remote monitoring	RFID based access products are already in the market RFID based location sensing are in development Printed temperature (and gas?) sensor is on the market Air, pressure, light printed sensors: concept demo in the lab
Displays (OLED)	6-7	Maturing technology	Printable backplane is the major challenge	Clear visually appealing signage Remote monitoring Improved communication with remote locations	Monitoring and interactive communication for remote locations on the premises/Electronic signage in full color	Inkjet printing technology is currently being developed – time to market – 5 years

PE-enabled solution	TRL level	Potential Market (e.g., units/building)	Tech readiness - development challenges	Drivers for adoption	End-user wants, needs	Next steps for market ready product (time to market)
Printed batteries	7-8	Technology is available but suitable for only for select applications. \$460 M market for thin, flexible and /or printed batteries by 2026 (IDTechEx)	The capacity is low with large 2-D dimension and is only suitable for special applications.	Cheap, flexible, small , lightweight batteries	Reliable disposable power supply	Commercially available
Biometric solutions	7	Access/wearable ID	N/A	Highly personalized high security access solution, not requiring a physical ID	Reliable on the spot identification method	RFID with printed antennas can be used. The technology is ready
Printed photovoltaics	7	Nanogrids, off-the-grid solutions		Cheap reliable power source	Customizable, scalable, effective reliable power supply	The technology is ready and currently in the stage of mass production development, cost reduction
Displays flexible	7	Electronic passports E-Readers Electronic paper Labels EL keypads Labels		Green solutions, better visibility, opportunity to change information displayed	Replacement for paper based solutions Security solutions that blend with decor	Commercially available

Table 4 Printable electronics and security and access TRL

7. MESHING IT ALL TOGETHER – COMMUNICATIONS PROTOCOLS

The most opportune time to add intelligence to a building is of course during the design and construction phases. But the reality is that, in the majority of cases, it will occur during a retrofit. The advantages of PE in terms of cost, form factor, and suitability to be part of a wireless or mesh network, mean that adding intelligence need not add undue cost or complexity to a retrofit project.

But how will all the sensor networks and building automation systems described in this paper communicate? Building automation and control systems are already becoming largely IP-enabled for networked communication. According to CABA, in 2013, IP-enabled controllers accounted for about 79 percent of total direct controllers sold in North America.

What standards will be used, considering that many PE-based solutions are low power and may have limited wireless range? A dominant communication standard for a networked building is BACnet. It was designed to allow communication for HVAC, lighting control, access control, and fire detection systems, and associated equipment. The BACnet protocol provides mechanisms for computerized building automation devices to exchange information, regardless of the particular building service they perform.

7.1. Wireless is gaining ground

Not long ago, the cost of wireless solutions for retrofit applications was prohibitive. But costs have come down. CABA's 2015 Market Sizing North America Report states that, considering the large number of buildings still using pneumatic building controls, connecting these automation and control systems with a wireless solution is the ideal retrofit solution.

7.1.1. ZigBee

The ZigBee standard is taking the lead in the North American commercial market. ZigBee is intended to be simpler and less expensive than other wireless personal area networks (WPANs), such as Bluetooth or Wi-Fi. Applications include wireless light switches, electrical meters with in-home-displays, traffic management systems, and other consumer and industrial equipment that requires short-range low-rate wireless data transfer. ZigBee devices can transmit data over long distances by passing data through a mesh network of intermediate devices to reach more distant ones. Mesh technology reduces redundancy and protects a network from disruptions caused by a single point of failure.

7.1.2. EnOcean

EnOcean devices work on the principle of energy harvesting, such as from sunlight, temperature difference, and movement. This aligns with the ultra-low electronics possible with PE and self-powered devices such as light controls or switches. The obvious downside is low-power signals that may not have enough strength for commercial purposes.

7.1.3. Z-Wave

Z-Wave is a wireless communications protocol geared more toward the residential home automation market that also minimizes power consumption. It is designed to provide

reliable, low-latency transmission of small data packets at data rates up to 100kbit/s, unlike IEEE 802.11-based wireless LAN systems (Wi-Fi) that are designed primarily for high data rates. This makes it ideal for embedded applications like remote controls, smoke alarms and security sensors.

7.2. Market-driven challenges

More information about other various wireless communication protocols that may be used in commercial buildings, including at the personal and local network level, is available in CABA's Connected Consumer Roadmap: Driven by the Internet of Things.

PE-based components and sub-systems have a role to play with the advancement of all of these wireless protocols. The challenge is for the PE technology companies to work with the building industry to develop products that meet the need of this market for reliability and security, and can be cost-effectively incorporated as part of either a new build or a retrofit. One example is printed antennas, for omnidirectional, wideband, and multi-band applications that would be cost prohibitive if realized by other means.

8. CONCLUSION

Based on the current state of PE technology and the advancements under development presented in this paper, PE can spur greater value and performance in the four main components of building automation systems. The common technology advancements in battery improvements, tailored sensors, and customized displays are fairly universal to all systems. These common core technologies will drive adoption of these technologies, as each advancement and reduction in price will cascade through all of these systems. PE can aid the performance of building automation systems, and in turn, help increase the value of commercial space. Investment in these core and non-core technologies is needed. Innovation of intelligent systems in integrated buildings will advance in part with the advancement of PE. Work remains to be done, in materials science and component and sub-system development, to produce PE options that can meet the needs of a commercial building environment, such as exposure to moisture, heat and wear. Systems that incorporate PE must also be certified to meet building codes.

But corporate and government research is already underway to bring these solutions to market. Advanced technologies like PE can help future concepts become real. Invisible sensors, flat batteries, embedded displays – these are all futuristic ideas that we will see in commercial buildings.



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