

The Design of an Integrated Sensing System for Various Applications

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Abstract – Designing a sensing system for varied applications leads to system choices and related details. A step-by-step design of an integrated sensing system is presented.

Key Words: sensors, systems, applications

1. Introduction

While there has been extensive literature published [1-6] presenting sensor technology fundamentals with an associated wide array of parameters being measured, the details involved in designing a sensor system are frequently not thoroughly described. Meanwhile, the need for increased availability of sensors to measure and monitor a wide variety of parameters has been widely reported in application areas ranging from environment tracking to industrial sites to local-, regional-, national-, and international-scale monitoring of climate variations. An example of such parameter sensing needs is outlined in the 2006 Stern Review: The Economics of Climate Change [7]. In this review, the measurement needs presented are strikingly similar to those measurement parameters associated with industrial operations: chemicals, biologicals, and classic physical parameters (temperature, pressures, etc.). Figure 1 presents three target applications that the sensing system design presented in this paper is tailored to.

Application	Sensors	Interface	Cost	Power	Packaging and environment
Indoor facility monitoring	Chemical Physical CO ₂	RF, mesh, RS-232/485	<\$500	Primary battery or External DC	IP54, 10 to 45 °C (indoor) Fix installed, 5-10 years
Security Perimeter monitoring	Biological Physical Chemical	RF, mesh, RS-485	<\$500	Solar + Secondary Battery or external DC	IP65, -20 to 55 °C (outdoor) Fix installed, 5-10 years
Cargo container truck/ trailer monitoring	Intrusion Chemical Motion	RF, mesh(?) or RS-485	<\$100	Primary battery	IP66, -40 to 75 °C Disposable or 1-5 years

* Diverse design requirements for the sensor module (no one size fits all solution)

Fig. 1. Possible applications for the integrated sensing system.

While there are multiple design and operational requirements that the integrated sensing system must

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meet (or approach), the power supply - in this case battery or solar - is paramount. Figure 2 presents voltages and charge capacities for a few batteries of varying sizes¹.

Type	Voltage	Capacity	Size	Cost (USD)
Lithium primary battery	3.6V	19 Ah@5 mA	D	\$20.8
		8.5 Ah@4 mA	C	\$16.2
		2.4 Ah@2 mA	AA	\$7.4
Lithium Ion secondary battery	3.6V	2.0 Ah@260 mA	18650	\$6.2
		1.1 Ah@220 mA	prismatic	\$2.1
Solar panel	4.8V	50 mA max	3" x 3"	\$11.9
		100 mA max	3" x 6"	\$22.9
Alkaline battery	1.5V	15 Ah@12 mA	D	\$1.68
		4.6Ah@ 12 mA	C	\$1.26
		2.0 Ah@ 12 mA	AA	\$0.54

Fig. 2. Battery power comparison.

Power consumption for a variety of sensors - and two inexpensive (low power, low computational capability) microcontrollers is presented in Figure 3².

Type	Voltage	Current	Power
Mesh radio	3.3V	20/ 30 mA	66/ 99 mW
Gamma sensor	3.3V	5 mA	17 mW
chemical sensor	4.5V	50 mA	225 mW
Passive IR Motion sensor	3.3V	300 uA	1 mW
Pressure sensor	3.3V	1 mA	3.3 mW
Accelerometer	5V	2 mA	10 mW
Hall Effect sensor	5V	3 mA	15 mW
Reed switch	N.A.	0	0
PIC18 MCU	3.3V	2 mA@4MHz	6.6 mW
MSP430 MCU	2.2V	280uA@1 MHz	0.6 mW

Fig. 3. Power consumption of various sensors.

From a power consumption perspective, the duty cycle associated with envisioned sensors being integrated into the system has a significant effect. Average power

¹ There are numerous types of batteries. Those presented in Figure 2 are simply representative.

² Popular microcontroller platforms such as Raspberry Pi (2/3/4 variants), Arduinos, Xiao's, etc are purposefully excluded.

consumption for various sensors, the two microcontrollers listed in Figure 3, and a generic radio - operating using a time-synchronized mesh protocol - are shown in Figure 4.

Type	On time	Cycle time	Duty	Avg Power	Comment
Mesh radio	2 sec	10 sec	20%	14 mW	90% receive, 10% transmit
Gamma sensor	3 sec	1 minute	5%	0.8 mW	
chemical sensor	3 sec	1 minute	5%	12 mW	
Passive IR Motion sensor	12 sec	1 minute	20%	0.2 mW	
Pressure sensor	always	always	100%	3.3 mW	Constant monitoring
Accelerometer	always	always	100%	10 mW	Constant monitoring
Hall Effect sensor	always	always	100%	15 mW	Constant monitoring
Reed switch	always	always	100%	0	Constant monitoring
PIC18 MCU	0.2 sec	1 sec	20%	1.3 mW	
MSP430 MCU	0.2 sec	1 sec	20%	0.2 mW	

* Duty cycle can make a big difference in average power consumption

Fig. 4. Sensors and communications duty cycles and average power.

2. Versions, Power, Packaging and Applications

Indoor and outdoor application settings - as well as varying levels of operational functionality led to this integrated sensing system having four different types of modules [8,9]. The estimated run time for each version assuming using a D cell battery as the primary power source are presented in Figure 5.

Module Type	Average power	Run time (primary, D cell battery)
Version 1: Radio	14 mW	4886 hours/ 203 days
Version 2: Radio + μ p + intrusion sensor	15.3 - 30.3 mW	4470 - 2257 hours/ 186 - 94 days
Version 3: Radio + μ p + CO2 sensor	16.1 mW	4248 hours/ 177 days
Version 4: Radio + μ p + chemical sensor	27.3 mW	2505 hours/ 104 days

Fig. 5. Sensor and operational configuration by Version with estimated operational time using a D cell battery.

Packaging of the system plays a significant role in developed sensor modules. Packaging is influenced by varying degrees by accessibility to components (maintenance and repair). Figure 6 shows five categories of module use.

Module Type	Power source	Packaging issue	Concerns
Disposable	Lithium	Sealed	Run time, disable when not in use(?), cost
Re-usable – replace battery	Lithium or alkaline	Accessible battery compartment	Weather proof seal, service (replace)
Re-usable – recharge battery	Lithium Ion or Lithium polymer	Charging contact	Weather proof seal, service (charging)
Solar with recharge battery	Lithium Ion	Solar panel & charging contact	Weather proof seal, cost
External power	AC or DC	Power connector	Weather proof seal, wiring cost

* Low battery indicator is a common issue for all module types, except external power

Fig. 6. Power source and packaging.

While market details may weigh heavily on the type of module used in the sensor system packaging, a cursory look at three applications - shown in Figure 7 - from an operations perspective leads to the "applicability rankings" shown in Figure 7.

Module Type	Indoor Facility monitoring	Security Perimeter monitoring	Cargo container Truck / trailer monitoring
Disposable	☹	☹	☹☹
Re-usable – replace battery	☺☺	☺	☺☺☺☺
Re-usable – recharge battery	☺	☺	☺☺
Solar with recharge battery	☹	☺☺☺☺	☹
External power source	☺☺☺	☺☺	☺

☺☺☺ – Best fit
 ☺☺ – Acceptable
 ☺ – Poor
 ☹ – Does not work

Fig. 7. Applicability of versions of sensors to envisioned applications.

While there are substantive variations associated with the components and subsystems that comprise the sensing system's module, Figure 8, aspects of wireless communications topologies (mesh, star, etc.), power source and class of sensors are dominant.

- 1. Mesh radio:**
 - Overhead (in ms) versus number of nodes and hops
 - Latency delay versus number of nodes and hops
 - Optimum duty cycle and cycle time
 - Performance indoors, outdoors and around metal containers
 - Robustness and self healing capability
- 2. Solar panel:**
 - Performance versus weather condition
- 3. Sensors:**
 - Selection of intrusion sensors
 - Chemical & radiation sensor performance

Fig. 8. Key components.

Four versions of module design have been decided via a standard down selection process. These versions, along with abbreviated categorization and operational descriptions, are shown in Figure 9.

Module	Description
Version 1	active RFID tag (or as an internal node of a mesh network)
Version 2	active RFID tag with built-in simple sensors
Version 3	Type 1 plus physical, chemical or external sophisticated sensors
Version 4	Type 2 plus local user interface functions

Fig. 9. Four sensor module versions have been identified.

The system building blocks - communications, power management, interface specifications, choice of sensor(s), and system interaction - are shown in Figure 10.

Building blocks	Version 1	Version 2	Version 3	Version 4
Short Range Radio w/ processor	yes	yes	yes	yes
Sensor interface/ power management	no	yes	yes	yes
Sensor processor w/ external sensor	no	no	yes	yes
Local user interface	no	no	no	yes

Fig. 10. Feature/performance version comparison.


2. Description and Comparison of Sensor Module Versions

There are obvious similarities in the versions of sensor modules. A systematic review of each module's functional and block diagram design reveals the similarities and differences.

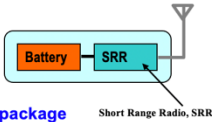
Version 1 is tailored for ease of installation with an understanding of disposability. Key aspects of Version 1's functionality and design guidelines are presented in Figure 11.

Version 1 Sensor Module

- completely sealed, battery (or DC) power, disposable package
- small form factor, easy to install
- very low cost (<\$20), long operating life (> 2 years)
- serve as active RFID and/ or a "connecting node" in a mesh network
- direct connection to an internal primary battery pack (or DC power for connecting node only)
- minimum user interface :power On/Off switch, battery low indicator (?)



size : 85 mm (L) x 56 mm (W) x 21 mm (H)



Short Range Radio, SRR

Fig. 11. Version 1 sensor module functions.

An associated block diagram of Version 1 is shown in Figure 12.

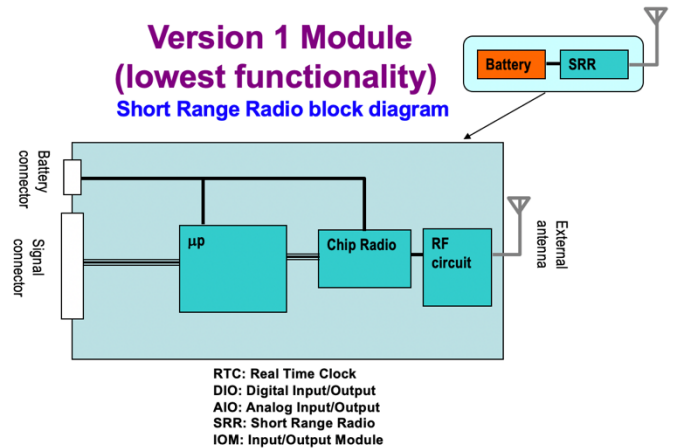



Fig. 12. Version 1 sensor module block diagram.

Version 2 is tailored for possible reusable packaging. Version 2 incorporates an input/output submodule but does not include a microcontroller. Key aspects of Version 2's functionality and design guidelines are presented in Figure 13.

Version 2 Sensor Module

- battery or DC powered, disposable or re-use package
- low cost (\$20 - \$70, sensor dependent)
- long operating life (> 1.5 years)
- serve as active RFID with analog sensor input
- Input Output Module (no µP) provides power management function, real time clock, data storage, electrical and mechanical interface to simple analog or binary sensor
- minimum user interface: power On/Off switch, battery or sensor status indicator (?)
- sensor supported:
 - ✓ pressure
 - ✓ proximity
 - ✓ Acceleration
 - ✓ motion
 - ✓ contact



size : 120 mm (L) x 65 mm (W) x 36 mm (H)

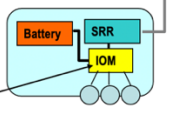


Fig. 13. Version 2 sensor module functions.

An associated block diagram of Version 2 is shown in Figure 14.

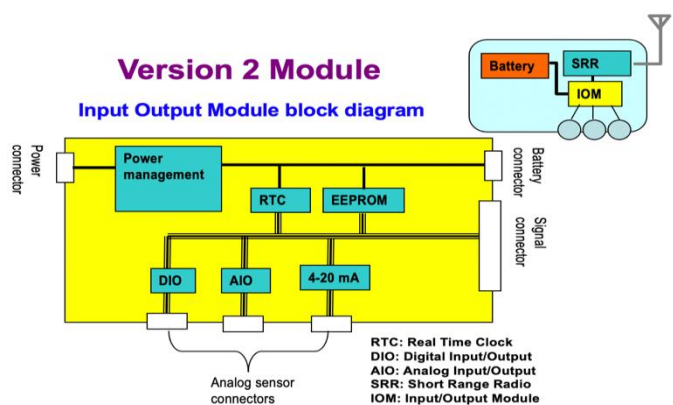
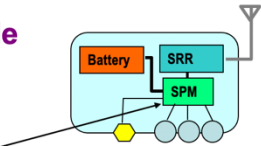


Fig. 14. Version 2 sensor module block diagram.

Version 3 expands on Version 2 by adding a sensor processor module (which incorporates a microcontroller/microprocessor). Note that a very limited computational "horsepower" processor was listed in Figures 3 and 4. In keeping with low power consumption, such a processor is incorporated. Key aspects of Version 3's functionality and design guidelines are presented in Figure 15.

Version 3 Sensor Module

- battery or DC powered, re-useable package
- medium cost (\$50 - \$100, sensor dependent)
- long operating life (> 1 years)
- serve as active RFID with analog and digital sensor input
- **Sensor Processor Module** (with μ p) provides power management function, electrical and mechanical interface to radiation, PID, digital (1451.4), analog and binary sensors, RS-232/485 interface
- minimum user interface: power On/Off switch, battery or sensor status indicator (?)
- sensor supported:
 - ✓ gamma, neutron
 - ✓ PID (chemical)
 - ✓ smart sensor (1451.4 compliant)
 - ✓ analog and binary sensor
 - ✓ CO₂, EC, CWA sensor (future?)



size : 121 mm (L) x 80 mm (W) x 55 mm (H)

Fig. 15. Version 3 sensor module functions.

An associated block diagram of Version 3 is shown in Figure 16.

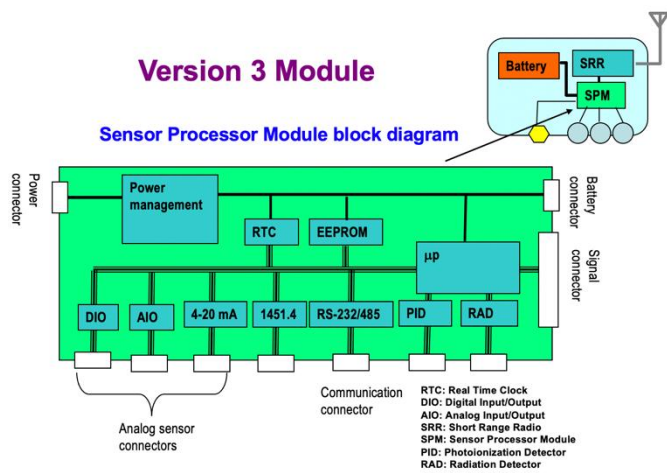
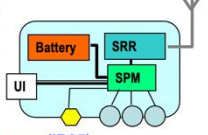



Fig. 16. Version 3 sensor module block diagram.

Version 4 presents a module with a user display and user interface capabilities. This module provides the user with a means of getting module readings directly. The enhanced module is shown in Figure 17.

Version 4 Sensor Module

- same as Version 3 module with local User Interface
- higher cost (\$70 - \$200, sensor dependent)
- ergonomically designed for indoor (IP54) and/or outdoor use (IP65)
- user Interface may include:
 - ✓ Power On/off switch
 - ✓ LCD display
 - ✓ LED indicator
 - ✓ Buzzer alarm
 - ✓ Push button or switch input
 - ✓ Infrared or magnetic non-contact input
 - ✓ RF wireless interface (Bluetooth, etc)
 - ✓ Relay contact output





size : 121 mm (L) x 80 mm (W) x 55 mm (H)

Fig. 17. Version 4 sensor module functions.

3. Sensor and Network Access

As the sensor modules become networked - and therefore become the integrated sensor system - each sensor module's method of access is important. The two access modes shown in Figure 18 are available.

Module	Description
Type A	Simple pass through access module from mesh network to host device
Type B	Intelligent access module between host/ networking and mesh network

Fig. 18. Integrated sensor modules modes of access.

A variety of wireless access devices have been designed for protocols including those reliant on RFID 802.15.4, 802.11 communications standards. In sync with the four versions of sensor modules, the two types of access methods selected are shown in Figure 19.

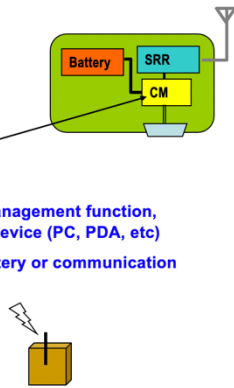
Building blocks	Type A	Type B
Short Range Radio w/ processor	yes	yes
Serial interface/ power management	Yes	yes
Communication processor	no	yes
Data buffering	no	yes
Protocol translation	no	yes
LAN interface	no	yes
Local user interface	no	optional

Fig. 19. Version 3 sensor module functions.

Figure 20 depicts the design functionality for the Type A access module. Note that Type A is designed to serve as a simple reader/interrogator communicating with sensor modules in a supervisory role.

Type A Access Module

- battery or DC (external or host powered)
- very small package (connect to a host device)
- low cost (\$30 - \$40)
- serve as simple reader attachment to a host device
- **Communication Module** (no μ p) provides power management function, serial interface (RS-232/485 or Bluetooth) to a host device (PC, PDA, etc)
- minimum user interface: power On/Off switch, battery or communication status indicator (?)
- host software supplied:
 - ✓ Adroid or iOS based
 - ✓ PedTech query and status display
 - ✓ diagnostic function (trouble shoot)
 - ✓ supervisory function (configure and program)



size : 60 mm (L) x 60 mm (W) x 15 mm (H)

Fig. 20. Functional overview of Type A access module.

An associated block diagram of the Type A access module is shown in Figure 21.

Type A Access Module

Communication Module block diagram

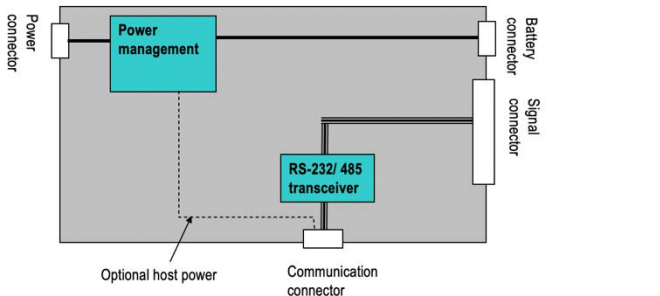


Fig. 21. Type A access module block diagram.

The Type B access module, shown in Figure 22, has considerably more complexity than Type A. Specifically a smart communication module capable of various levels of bi-directional information transport is added to the design. An enhanced user interface capability - in software and hardware - allows the Type B to function as a stand-alone sensor module network reader/interrogator or to operate as a gateway to the host system.

Type B Access Module

- battery or DC (external or host/ network powered)
- small package (stand alone, connect to a host device or a networking device)
- medium cost (\$80 - \$350, interface dependent)
- serve as stand alone reader or as a gateway to a host device and/ or a long haul communication network
- **Smart Communication Module** (with μ p) provides power management function, serial interface (RS-232/485, Ethernet or Bluetooth) to a host device (PC, PDA, embedded server, etc) or a long haul networking access device (LAN, GPRS modem, ISM industrial modem, WiFi, etc), etc.
- medium user interface: power On/Off switch, battery and communication status indicator, optional programming interface (keyboard/ display)
- embedded firmware includes:
 - ✓ Apprion interrogation and supervisory function
 - ✓ protocol translation and data buffering
 - ✓ host/ networking interface
 - ✓ local user interface

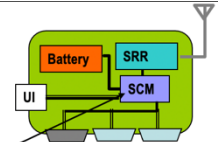


Fig. 22. Functional overview of Type B access module.

An associated block diagram of the Type B access module is shown in Figure 23.

Type B Access Module

Smart Communication Module block diagram

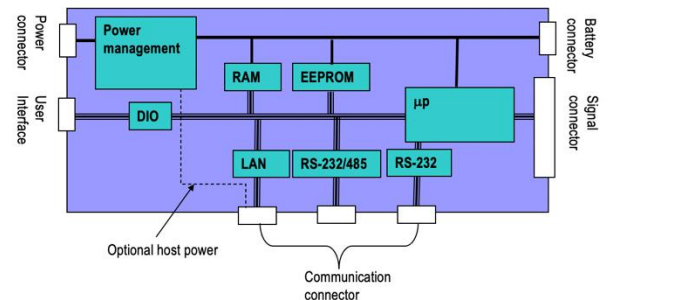


Fig. 23. Type B access module block diagram.

Type B provides opportunities for a variety of access methods using the wired and wireless connectivity options. Three such access methods are illustrated in Figure 24.

Type B Access Module

Access Methods:

- ✓ **1. Hand held smart reader:**
 - simple user interface (LCD, key pad)
 - status, control and diagnostics
 - size : 100 mm x 60 mm x 20 mm
- ✓ **2. Fixed installed wireless smart reader:**
 - integrated with long range industrial wireless modem for wireless backbone
 - support variety of protocols translation
 - size : 150 mm x 70 mm x 50 mm
- ✓ **3. LAN access smart reader:**
 - plug directly into RJ-45 connector
 - power over Ethernet
 - size : 80 mm x 60 mm x 50 mm



Fig. 24. Various methods of sensor module access.

Of particular note, is that the Type B access method utilizes a cellular link, Figure 25. There are a variety of cellular standards/protocols that can be used including 4G/LTE, 5G or proprietary schemes.

Type B Access Module

Access Method:

✓4. Smart reader with cellular link:

- programming user interface (LCD, key pad)
- integrated cellular modem
- hand held or dash board mount
- battery or DC powered
- size : 110 mm x 60 mm x 40 mm



Fig. 25. Functionality of cellular-based access method.

The completed, integrated sensor system is designed to provide simple and robust aggregation of measurements/data from the sensor modules. From a network access and system management perspective, the sensing system server provides sensor status and remote alarm notification - as well as measurements - to higher level applications. Thus, an application programming interface is required. All information and measurements may be stored locally (on the server) or ported to, for example, a cloud-based database repository.

Sensing System Server

- external DC or solar powered w/ backup battery
- indoor or outdoor (weather proof) package
- medium cost (\$1,000 - \$1,500)
- serve as simple and robust local server to aggregate data from sensor nodes, allow internet access to sensor status and remote alarm notification
- **Embedded Server Module** (with μ p) provides power management function, multiple interface (RS-232/485, LAN, USB, PCMCIA, etc), local storage, video camera
- minimum user interface: power On/Off switch, communication status
- host software supplied:
 - ✓ embedded Linux with built-in web server
 - ✓ query and sensor data storage
 - ✓ remote live video display (optional)
 - ✓ remote alarm notification via internet
 - ✓ remote diagnostic and supervisory function via browser



size : 150 mm (L) x 100 mm (W) x 50 mm (H)

Fig. 26. Functionality of integrated sensor system server.

4. Possible Deployment Architectures

The applications highlighted in Section 1 anticipate deployment of the integrated sensor system in both indoor and outdoor environments. In addition, the deployment site may or may not have a wired or wireless backhaul network. Figure 27 illustrates an anticipated layout for a Version 3 (sensor module) plus Type B (access module) along with the sensing system server.

Facility (Office/ Plant) Deployment Example

- Version 3 (x12): physical sensor, battery power
- Access B2 (x3): 900 MHz wireless, DC power
- ⬡ Server (x1): 900 MHz wireless, DC power

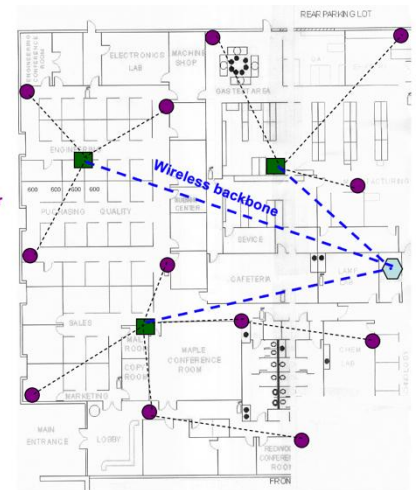


Fig. 27. Proposed deployment of integrated sensor system in an office facility.

A similar deployment layout utilizing a wired (Ethernet) backhaul network is shown in Figure 28. Access and sensor modules each with mesh networking capability allow for ease of deployment configuration. Note that the Sensing System Server may be located anywhere along the backhaul network (in this instance a wired Ethernet backbone).

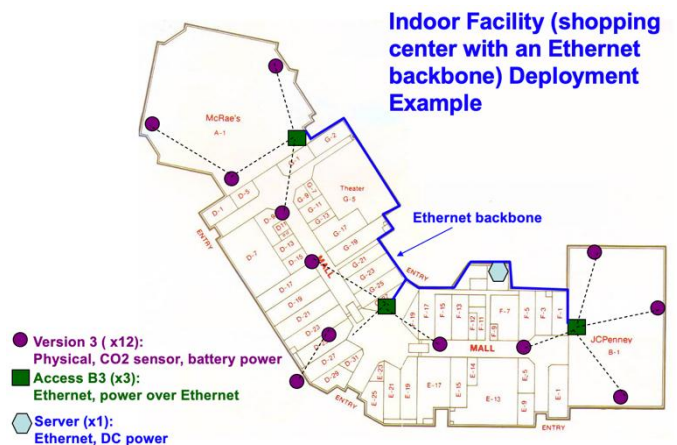


Fig. 28. Proposed deployment of integrated sensor system in an indoor shopping center with wired Ethernet backbone.

A deployment envisioned for a hotel or convention center is a further variant on those shown earlier. As shown in Figure 29, a wired backhaul network does not exist. Therefore, a wireless backhaul network comprised of numerous Sensing System Servers which operate in a bridge mode with each other to establish the resilient backhaul network. These devices are placed at locations within the deployment site where a stable communications link is established.

Facility (hotel with WiFi backbone) Deployment Example

- Version 3 (x12): Physical, CO2 sensor, battery power
- Access B3 (x3): Ethernet, power over Ethernet
- Server (x1): Ethernet, DC power

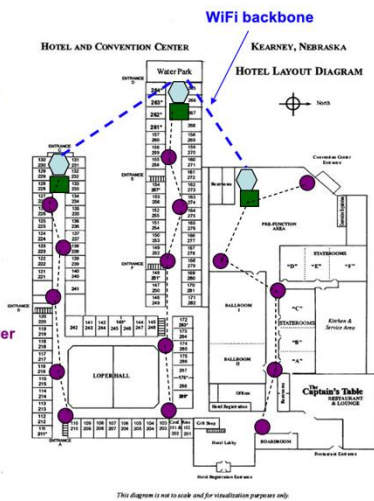


Fig. 29. Proposed deployment of integrated sensor system in a hotel/convention center with Wi-Fi backbone.

The deployment configuration for outdoor an outdoor setting where perimeter security and sensing is required is illustrated in Figure 30. The sensor modules (Version 3) communicate with each other with, in this instance, two access modules communicating with the in-range sensor modules. The access modules are connected by a serial link to the Server.



Fig. 30. Proposed deployment of integrated sensor system in an outdoor perimeter sensing and security location.

5. Summary

The design of a modular integrated sensing system has been presented. The modular design allows for varying levels of complexity sensors, access devices and server capabilities to be tailored for the deployment application. Therefore, given the overlapping sensing needs, technological solutions developed for operation in one setting (or application) may be well suited for easy adoption into an entirely different setting. In all cases, the use of communications and networking technologies allow for measurements to be obtained and catalogued via

remote access, thereby removing the cost and time associated with fieldwork sampling.

6. References

1. E. P. K. Gilbert, B. Kaliaperumal and E. B. Rajsingh, "Research Issues in Wireless Sensor Network," International Journal of Information and Electronics Engineering, pp. 702-706, September 2012.
2. I. F. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, "A survey on sensor networks," Communications Magazine, pp. 102 - 114, Aug 2002.
3. Rawat, P., Singh, K.D., Chaouchi, H. et al. Wireless sensor networks: a survey on recent developments and potential synergies. J Supercomput 68, 1-48 (2014). <https://doi.org/10.1007/s11227-013-1021-9>
4. R. O. Saber, A. Fax and . R. M. Murray, "Consensus and Cooperation in Networked Multi- Agent Systems," Proceedings of the IEEE, vol. 95, no. January, pp. 215-233, 2007.
5. Römer, Kay; Friedemann Mattern "The Design Space of Wireless Sensor Networks" IEEE Wireless Communications, Dec. 2004.
6. V. Raghunathan, C. Schurgers, S. Park, and M. B. Srivastava, "Energy-Aware wireless Microsensor Networks", IEEE Signal Processing Magazine, 19 (2002), pp 40-50.
7. Stern, N. "Stern Review on The Economics of Climate Change (pre-publication edition). Executive Summary". HM Treasury, London, 2006. Archived from the original on 31 January 2010.
8. Wendi B. Heinzelman, Anathan P. Chandraskan, and Hari Blakrishnan, "An Application-Specific Protocol Architecture for Wireless Microsensor Networks", IEEE Trans. on Wireless Communications, 1 (4): 660-670, OCT 2002.
- 89 Lim, Cheng Leong A "n approach to understand network challenges of wireless sensor network in real-world environments", Univ of Glasgow, PhD dissertation 2019.