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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 throughly 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 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 sizes[1].

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

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 perspecive, 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 + μp + intrusion sensor	15.3 - 30.3 mW	4470 – 2257 hours/ 186 – 94 days
Version 3: Radio + μp + CO2 sensor	16.1 mW	4248 hours/ 177 days
Version 4: Radio + μp + 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 in influenced by varying degrees by accessiblity 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.

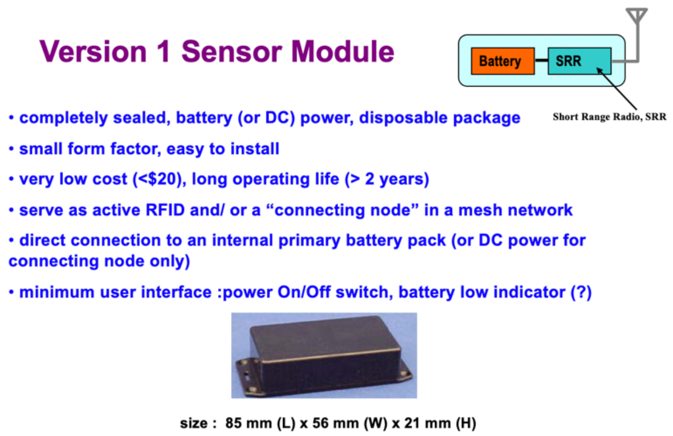

Fig. 11. Version 1 sensor module functions.

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

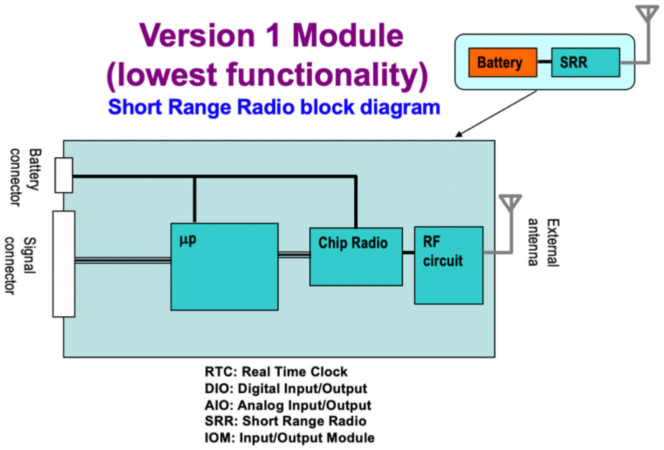

Fig. 12. Version 1 sensor module block diagram.

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.

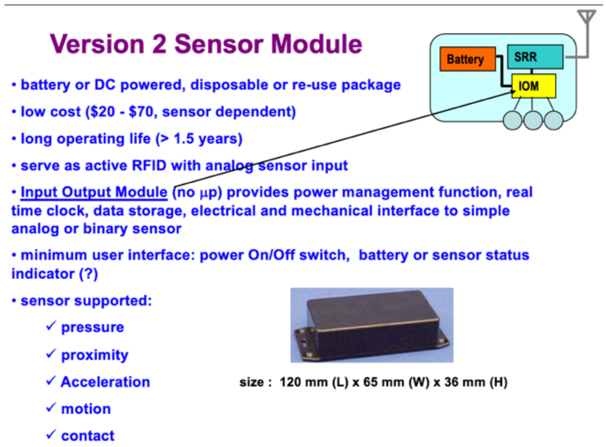

Fig. 13. Version 2 sensor module functions.

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

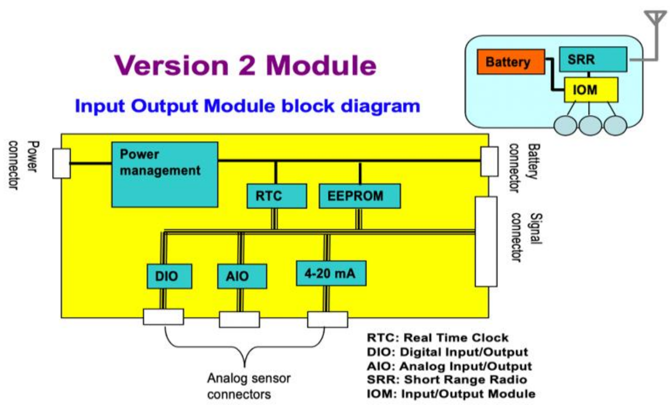

Fig. 14. Version 2 sensor module block diagram.

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.

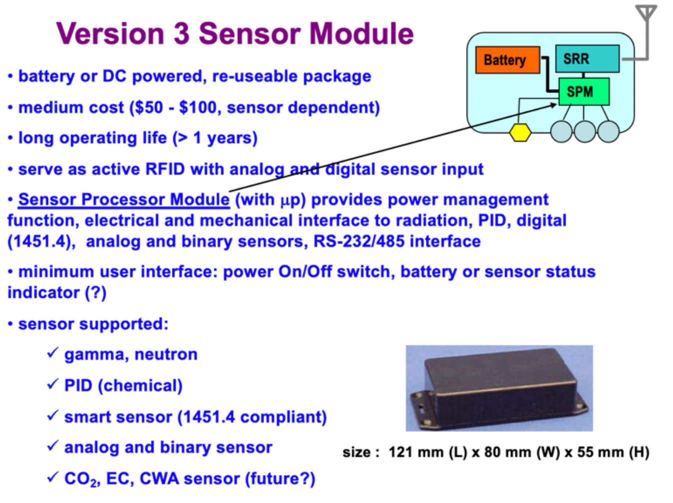

Fig. 15. Version 3 sensor module functions.

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

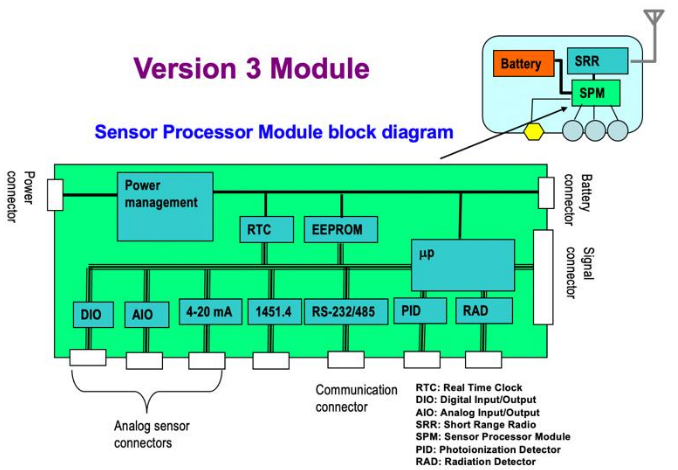

Fig. 16. Version 3 sensor module block diagram.

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.

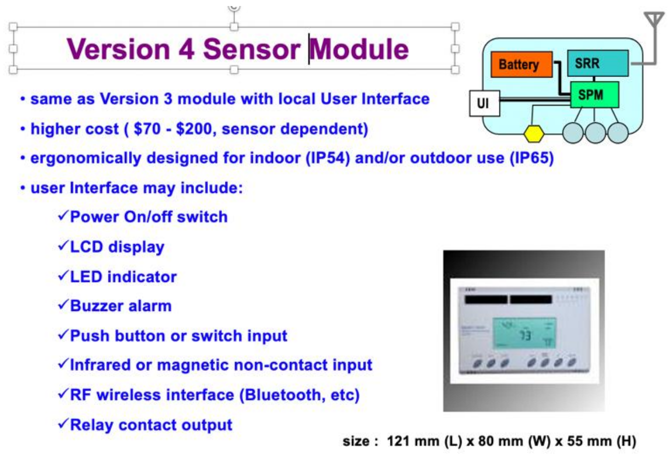

Fig. 17. Version 4 sensor module functions.

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 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.

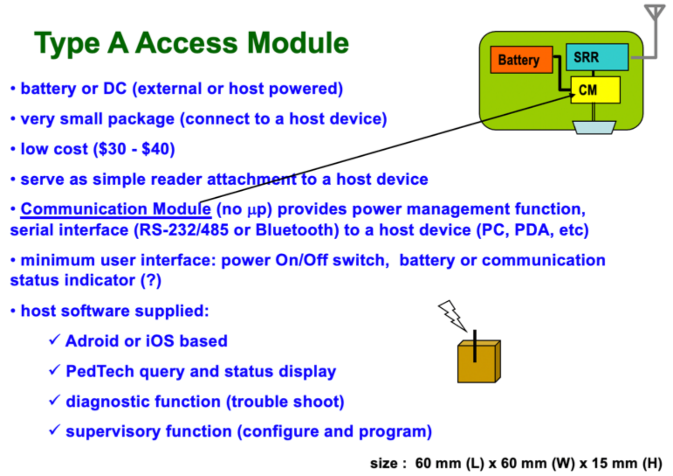

Fig. 20. Functional overview of Type A access module.

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

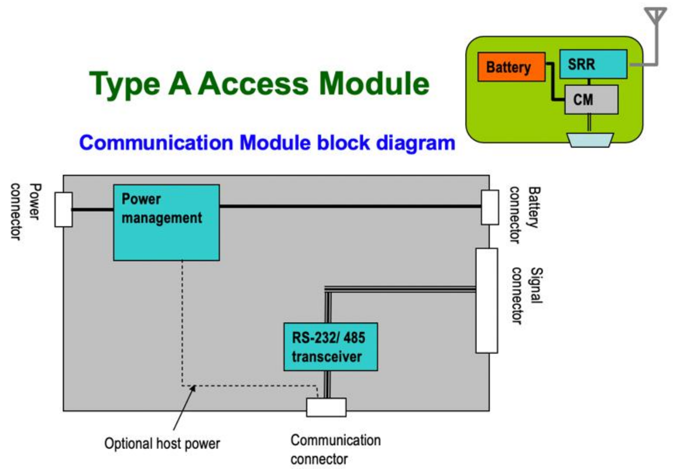

Fig. 21. Type A access module block diagram.

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.

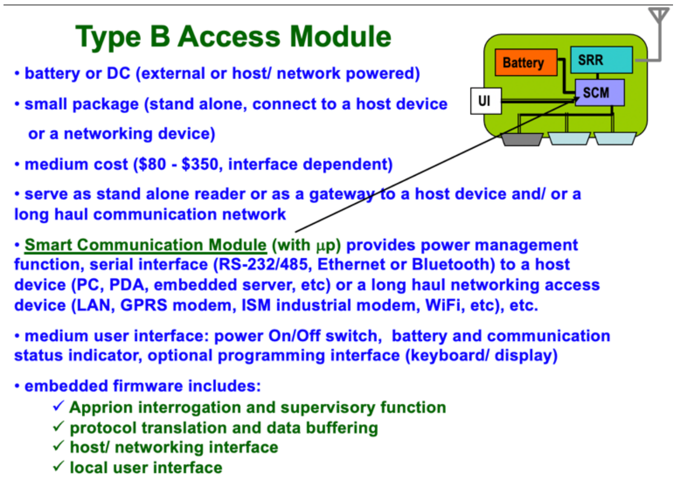

Fig. 22. Functional overview of Type B access module.

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

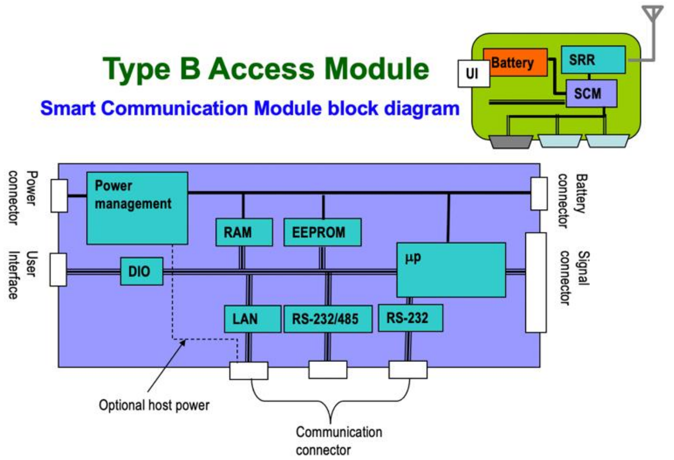

Fig. 23. Type B access module block diagram.

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.

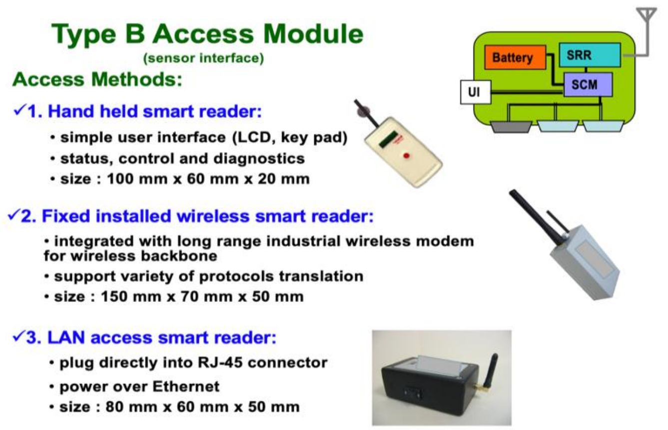

Fig. 24. Various methods of sensor module access.

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.

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.

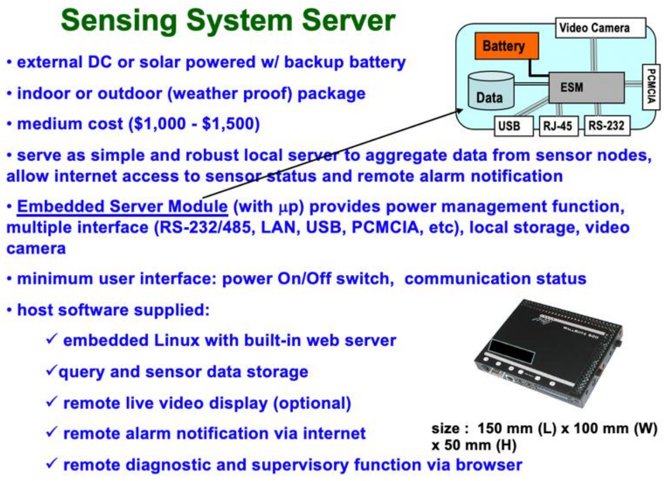

Fig. 26. Functionality of integrated sensor system server.

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.

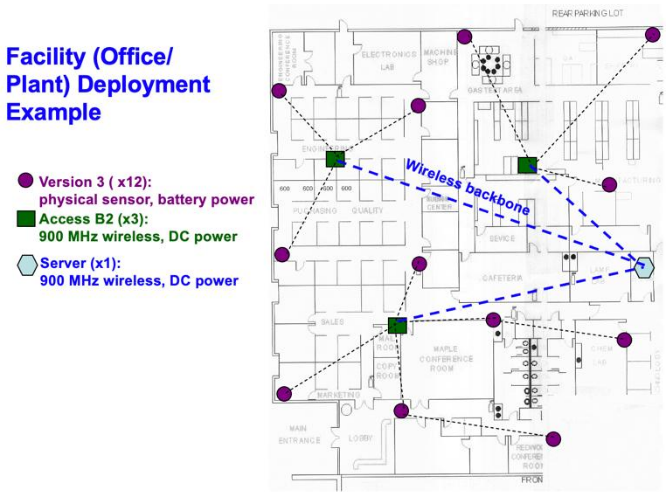

Fig. 27. Proposed deployment of integrated sensor system in an office facility.

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).

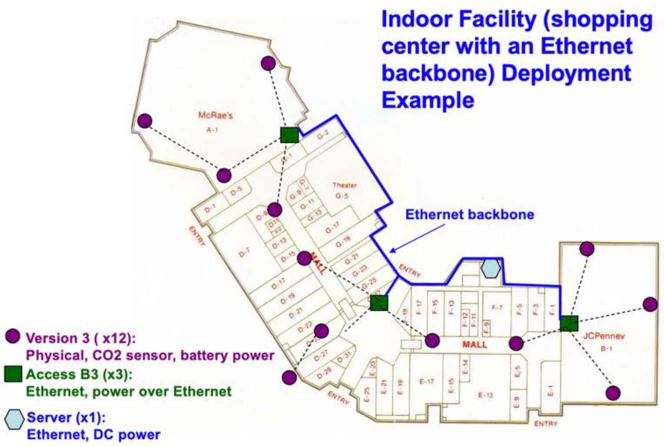

Fig. 28. Proposed deployment of integrated sensor system in an indoor shopping center with wired Ethernet backbone.

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 exsit. 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.

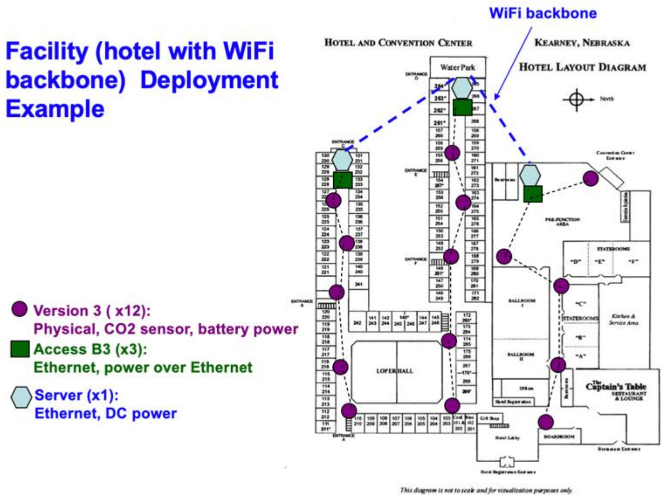

Fig. 29. Proposed deployment of integrated sensor system in a hotel/convention center with Wi-Fi backbone.

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.

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