

Sensor Network Hardware Infrastructure for Smart Spaces

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1. Introduction

Like people, a “smart space” can only produce reactions based on the information it receives. Some of this information will be “active” i.e. deliberately transmitted by a user e.g. electronic information from personal electronic devices or voice commands. The user will in general expect a specific response from the smart space. At a more advanced level, however, the “adaptive” or “context aware” smart space, if it is to anticipate a user’s requirements or manage the space in the absence of users, needs to be equipped with its own means of gathering information. To do this, it uses sensor networks. Just as “smart space” has many different meanings and applications, so has “sensor network”. At a very basic level, a deployment of temperature sensors used to control individual room

heating in a house is a sensor network which creates a “smart space”. However, when this network is extended to monitoring the number of people in each room, their activities, the external climate and the information is used to select the most energy efficient method to set a comfortable temperature based on the recorded or learnt preferences of the users, then the more advanced term of “adaptive smart space” applies. Without a sensor network, a smart space cannot be truly adaptive.

Within the confines of a building, regardless of the complexity of the sensor network, the boundaries of the network are clear and its deployment and monitoring is relatively straightforward. Extend the smart space outside fixed boundaries and the problem becomes more complex. Considering a scenario such as monitoring the position, limb motion and medical

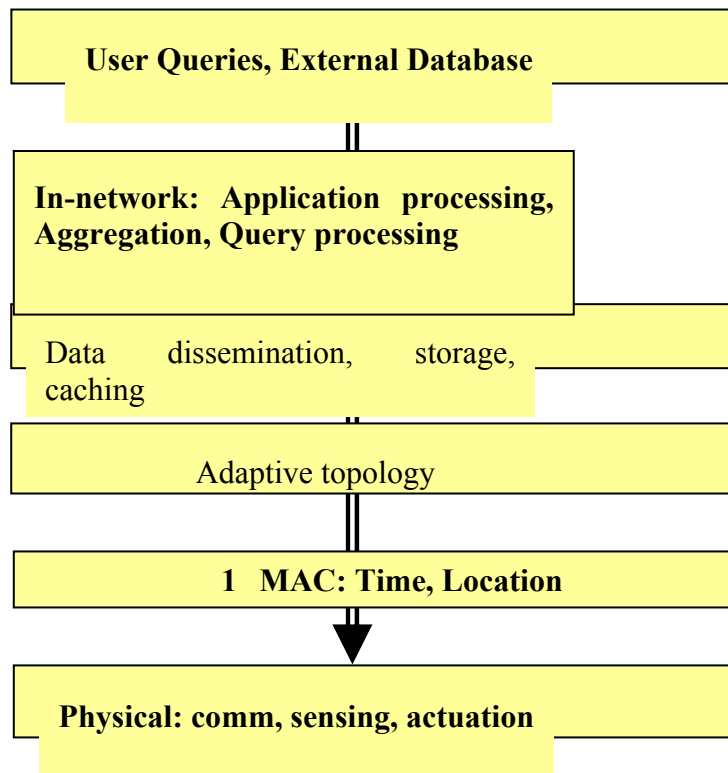


Figure 1: Sensor network protocol stack

vital signs of all the competitors in a triathlon gives a picture of the degree of complexity involved and the scope of the term “sensor network”.

It is possible, however, to generalise the problem to examine the challenges which are common to almost all sensor networks for adaptive smart spaces. The typical sensor network protocol stack is shown in Figure 1 [1].

From a hardware infrastructure aspect, this paper will concentrate mainly on the bottom layer – the actual sensing node – and the higher layers will be considered only for their impact on the hardware. The main hardware challenges can be listed as:

- suitable sensor nodes
- deployment of the sensor nodes
- powering of the sensor nodes
- data collection
- sensor node location detection
- updating or reconfiguration of the deployed network

In this paper, we will examine these generic challenges and some specific solutions, with the

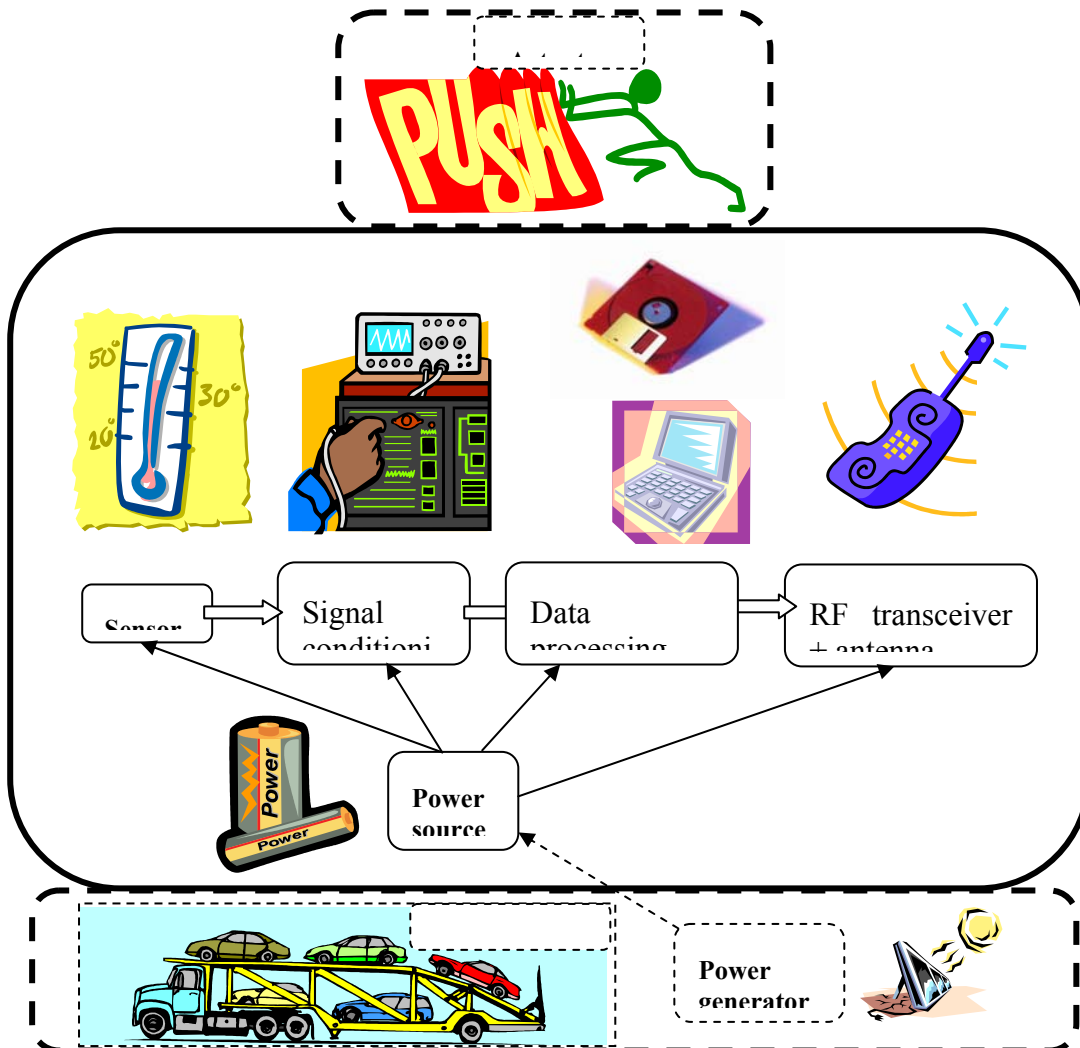
focus on the hardware aspects of wireless sensor networks. In particular, we will discuss the capabilities of ultra wideband (UWB) wireless technology and its advantages for sensor networks.

2. Sensor nodes

A “node” is a standalone module capable of transmitting sensor data. It may be a “deaf node” with only data transmission capabilities or it may be capable of interactive communication with other nodes or a central control unit. As shown in Figure 2, a node must have a minimum set of essential core components (solid lines) and optional components can be added depending on the application requirements (dashed lines). For wireless sensor networks, the power source is usually a battery and a primary concern in node design is that of minimising power consumption. Typically, size and cost minimisation are the next most important design concerns.

2.1. Essential components

Sensor With the growth in recent years of microsensor, biosensor and MEMS technology



(generically termed “microsystems”), the scope of what can be sensed by a sensor network has increased enormously. There are few common physical, environmental, chemical, biological or medical measurands for which there is not a small, light, low cost, low power integrated sensor available or under development in research labs. It is also possible to combine microsensors with microactuators so that, taking for example the human body as a smart space, it is possible to use transdermal sensors to monitor both drug levels in blood and a patients physical activity. This data can then be used to control a transdermal drug infuser. The sensor network may also relay this data to a medical monitoring system allowing recording of patient medical data or alerting of the patient or a doctor if a health risk is identified. The range of possibilities offered by microsensors and microactuators is being actively used and investigated by the ambient intelligence community [2]. From a wireless sensor node aspect, the primary advantages are the low power and small size aspects of microsystems. The increased reliability and ruggedness associated with many microsystems also increases the possible range of smart space applications.

Signal Conditioning is required to transform the sensor output to a format, usually digital, compatible with data storage and processing. Typically, this implies amplification and A/D conversion. The ability to integrate microsensors on integrated circuits facilitates sensor ICs with amplified or digital outputs.

Data Storage and Processing is typically done by a microcontroller IC. There are many different types available on the market, some optimised for low power consumption, with a wide range of data input, program storage and data storage options.

the RF transceiver, typically the highest power consumption component of a node, to spend most of its time in sleep mode, thereby reducing overall node power consumption. Some microcontrollers are now coming on the market with integrated RF transceivers, further reducing sensor node size. Most microcontrollers feature power saving idle and sleep modes which can be exploited by sensor node designers. A number are also available in minimally sized chip scale package (CSP) format.

As well as data storage, the microcontroller will also usually take care of the RF communications protocol and carry out digital signal modulation or coding if required before sending.

RF Transceiver Advances in mobile communications and in wireless data transfer have spun off a wide range of wireless data transceiver ICs. These superimpose the digital data from the microcontroller onto an RF carrier for transmission and vice versa for reception. Some are optimised for sensor data transmission with a design emphasis on low power consumption and on the low data rates typical of wireless sensing applications. It is possible to get RF transceivers for all of the unlicensed ISM bands commonly used in sensor networks.

Antenna While some progress is being made towards integration of antennae onto transceiver ICs for short range applications, an external antenna is largely still required for sensor nodes. This may typically be a planar antenna on a circuit board or a miniaturised surface mount component, as opposed to a protruding antenna. These can, however, also be used depending on the application. As the antenna size typically decreases with increasing frequency, there is a tendency to use higher frequencies for transmission. This, however, has to

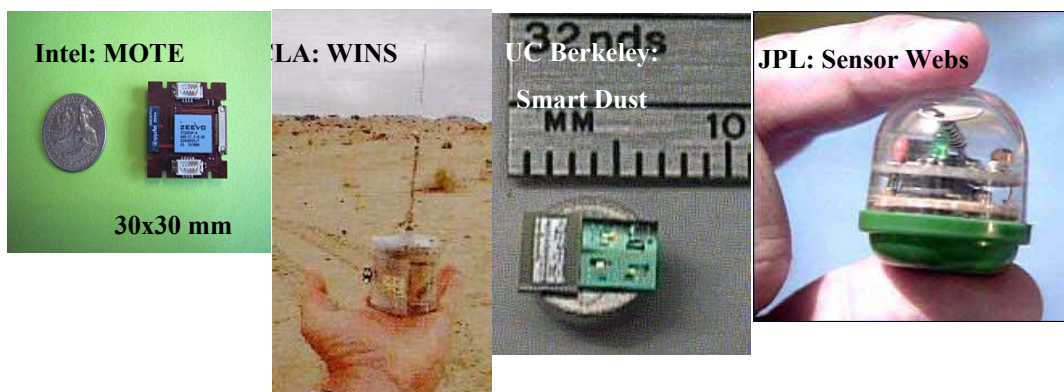


Figure 3: Sensor nodes from Intel, UCLA, Berkeley and JPL

Many are also available On-board data storage is particularly useful because it means data can be stored for later wireless transmission. This allows

be offset against higher propagation path loss at higher frequencies leading to a need for higher power transmissions and shorter battery life. Ultra

wideband technology has much to offer from this aspect, as is discussed in Section 5 below.

Power source This is most typically a battery. Again, advances from mobile communications battery research have led to higher energy densities and longer battery life. Small sized batteries capable of powering a sensor node for long periods are therefore readily available at reasonable cost. There are also emerging planar batteries on rigid or flexible materials [3], even paper [4] and fabric [5], which make integration with the usually planar structure of sensor node hardware easier. Many of these batteries are rechargeable with a capability for a high number of recharge cycles.

2.2. Non-essential components

Power generator Where it is impossible or inconvenient to replace a battery in a sensor node or to remove it to a recharging station, some form of integrated power generation is required to supplement the main battery. The main methods available are based on energy transducers which convert other energy forms (e.g. vibration, motion, light or heat if available in the application), on ambient electrical/magnetic energy or on electrical/magnetic energy transmitted from a central hub. Table 1 gives an indication of the typical power available from various sources [6].

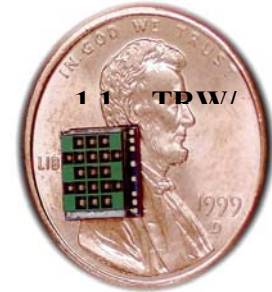
Sensors attached to moving or vibrating objects are the easiest to deal with because of the large mechanical energy inputs. The main challenges are to minimise the size of the transducer, generally

through MEMS technology, and to maximise its efficiency. Sensors attached to a warm surface or exposed to bright light facilitate recharging through thermoelectric generators or solar cells, both sources of relatively high power.

Fixed sensors in the dark set the greatest challenge and, if they are remote from the sensor network controller it is impossible to safely transmit sufficient energy to maintain a charged battery. In this case, nodes optimised for very low power

consumption combined with a suitable battery can still achieve years of operation on a single battery. The overall sensor network topology must also be optimised so that the power consumption of individual nodes is minimised. This is typically achieved through the formation of an ad-hoc sensor network where data is relayed short distances from one node to its neighbour until it reaches the central controller.

Transporter This largely applies where sensor nodes are deployed on robots. Where the sensor node is required to track a particular object or phenomenon e.g. track down a pollution source by following an increasing pollutant concentration



Packaged MEMs microthruster actuator

Energy Source	Transducer	Typical output Power/cm ² of transducer
Walking (impact)	Piezoelectric	5W
Walking (vibration)	Discrete moving coil	400μW
Thermal	Thermoelectric	30mW (25°C gradient)
Solar	Photovoltaic cell (outdoor)	20mW
Magnetic field	Coil	1.5mW
High frequency vibration	Integrated moving coil	100μW
Acoustic noise	Microphone	3x10 ⁻⁶ mW/cm ² at 75dB 10x10 ⁻⁴ mW/cm ² at 100dB
Background RF fields	Antenna	5μW
Transmitted RF field ¹	Antenna	???mW ¹

Table 1: Supplementary power for sensor nodes from various sources

gradient then the output of the node can be used to direct a robot transporter. Intel are examining potential applications using plant care as a trial application [7].

Actuator For a smart space to be truly adaptive and intelligent, it should be able to autonomously control physical aspects of itself. This might simply, as mentioned in the introduction to this paper, consist of using electrical switches to control heating to maintain a required temperature. At a more complex level, the node itself may itself contain an actuator such as the microthruster shown here which could conceivably move the node itself about. The range of microsystems actuators available matches that of microsensors and opens a huge range of new possibilities for sensor network technology.

2.3 Example nodes

Figure 2 shows a selection of sensor nodes from various sources.

A node has also been developed in a CIT research project (Supported by Enterprise Ireland under the Applied Research Grants Programme) containing all of the essential node components on a 19x19mm PCB. This node works at 433MHz and a second node of approximately the same size, working at 902MHz and capable of operating in a multi-channel frequency hopping sensor network is also completed. An ultra-miniaturised third node, incorporating both essential and non-essential components, is currently at the design stage.

3. The sensor network

The control and topology of the sensor network can range from the very simple to the complex. Detailed discussion is beyond the scope of this paper other than how it impacts on the hardware infrastructure, particularly the sensor node power consumption and size.

3.1. Static nodes

- individual static nodes communicating only to a central controller which does all of the data processing and decision making. This reduces the processing power required in the nodes, and hence the node power consumption for that purpose. However, transceiver power consumption will be higher because of the requirement for every node to transmit to the central controller. The transmission power of each node can, however, be minimised as the distance from the node to the central controller is predefined.
- limited local processing and decision making in static nodes monitored by a central controller with communications only between

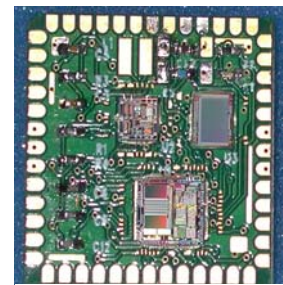
the individual nodes and the controller. Despite the increased processing power required in the node, this may be more power efficient because the node will probably spend less time communicating with the central controller.

- multi-hop communication from static node to static node based on predefined routes. Careful route detection and planning will be required because, even though each node is transmitting a shorter distance, and hence reducing its transceiver power, it will spend more time transmitting because it has to relay the data of other nodes as well as sending its own.

3.2. Mobile nodes

All of the networking topologies described for static nodes above can also be used for mobile nodes and it is possible for nodes to adjust their transmission power dynamically based on estimating their distance from the central controller by detecting carrier signal strength. A network with mobile nodes also has additional possibilities:

- based on the position of the nodes, the central controller can dynamically reconfigure the hopping route to minimise power consumption in the network. It can also reconfigure in the event of a node failure or the entry of new nodes into the network. This may be the most power efficient methodology as the central controller can implement complex power management algorithms beyond the processing capabilities of individual nodes.
- in the most complex sensor network, the sensor network becomes a full mobile, ad-hoc, multi-hop network where each node stays aware both of its own position and that of its neighbours and makes its own decision as to choice of route to the destination node. The central controller may itself be mobile or in the most extreme case there is no central controller and intelligence is distributed throughout the sensor network. To save battery power in such a network, the nodes must be turned off as much as possible but turning off nodes for an extended period increases the likelihood of a node missing and dropping packets. To prevent this, network nodes should turn off and power up in a coordinated manner. This requires solving several design issues across the MAC,



CIT 433MHz node

network and application layers in the protocol stack [3].

Self-aware and self-configuring sensor networks are the subject of much theoretical research but they present one additional hardware challenge, if a space is to be truly “smart”: the requirement to detect the position of the sensor.

4. Position detection in sensor networks

Position detection is required not only for locating nodes in a smart space with a reconfigurable sensor networks but also for the more general problem of tracking objects moving in the smart space. Positioning systems can be classified as follows:

- Absolute position on geoid e.g. GPS
- Location relative to fixed beacons e.g. LORAN
- Location relative to a starting point e.g. inertial systems
- Most applications:
 - location relative to other people or objects, whether moving or stationary, or the location within a building or an area

In all cases the range and resolution of the position location needs to be proportionate to the scale of the objects being located.

Systems such as GPS, although offering high resolution, have limited application in wireless sensor networks because of high node power consumption. In some situations, e.g. tracking people walking about, pressure sensors in the floor and in furniture can be used to track location in 2-D space with sufficient accuracy to allow some adaptivity. Location relative to a starting point can be accurate for sensor nodes, especially with the availability of MEMs gyros and accelerometers. While the power consumption of the node is increased considerably this may be compensated by using movement to generate power in the node. Like all inertial systems, however, they are prone to drift and need to be reset to some known starting point at intervals.

It is possible to use optical positioning providing the object to be located is suitably reflective and displays its reflectivity on a constant basis. However, lasers are required for accuracy and these must be scanned to cover an entire 3-D space, which is impractical for most consumer applications and relies on line of sight. Video imaging, combined with image analysis, can allow positioning with high precision but the video quality and processing power required makes the system very expensive. It will also generally be bulky and intrusive.

It would be ideal if we could minimise positioning hardware overhead by using the RF signals from wireless nodes in a triangulation based system, typically by using at least three fixed beacons which measure received signal strength, angle of arrival or time of flight differences.

- Received signal strength relies on having a detailed propagation path model for the entire 3-D space. This is almost impossible in a sensor network with mobile nodes e.g. when people are moving about continuously. It is also restricted by multiple access interference. There is also difficulty with non-line of sight nodes.
- Angle of arrival is restricted by multipath propagation and scattering problems. It also has difficulty with very small or large angle spreads and non-line of sight nodes.
- Most commonly used RF protocols and modulations do not readily lend themselves to time of flight calculations either because it is inherently difficult to extract relative times from them or because of difficulties caused by multipath fading.

There is, however, one RF technique which not only lends itself to highly accurate positioning but also offers many other advantages for wireless sensor networks: ultra wideband (UWB).

5. Ultra Wideband communication

5.1. Introduction

Wideband in this case refers to signals with large fractional bandwidth – up to 25% or more (or 500MHz or more) compared to the very small fractional bandwidths of typical communications systems such as GSM. UWB communication has been around for a long time - the very first radio transmission by Marconi using spark gaps as transmitters was inherently wideband. UWB has also been used for short range radar applications such as ground penetrating radar because of its inherent ability to propagate through solids. However, because UWB signals require more complex signal processing than narrowband systems it has been necessary to wait for modern high speed analog and digital electronics to allow low cost implementation for communications. UWB is now, however, the subject of active research for a wide range of applications..

From a sensor network aspect, UWB has many advantages. Most RF signals are analysed in the frequency domain. However, UWB signals, because of their nature, are more accurately described in time domain. UWB systems are based on transmission of very short (sub-ns) electrical pulses in time and that way they spread their power

spectrum over many frequencies (a different approach to narrowband systems where energy is spread in time but focused in the frequency domain). This gives unique features those are unattainable with another systems. Figure 3 shows typical UWB Gaussian or Gaussian monocycle pulse.

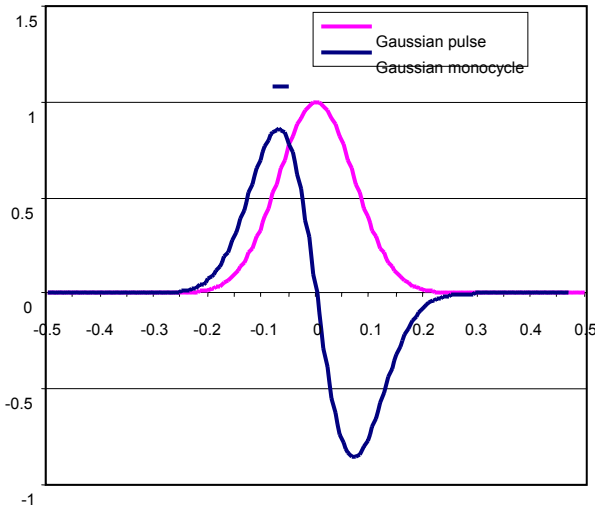


Figure 4: Gaussian and Gaussian

UWB:

- The time of flight is precisely measured by the phase shift of the code. The receiver locks to the coded sequence of the transmitter within an accuracy of less than 100 picoseconds and a resolution of about 3 cm.
- Its immunity to fading and hence to changes in the physical environment of the smart space e.g. movement of furniture or people
- The ability of a UWB receiver to discriminate between direct and multipath propagation signals, as indicated in Figure 4.

There are even further advantages for sensor networks [9]:

- The power awareness and efficiency of such systems is much better than traditional narrowband system. For example Bluetooth quality of service can be obtained with less than 100 times transmitted power.
- The power spectral density of a UWB signal is very low (according to FCC rulings less than -40dBm/MHz [10]) which is in the level of the ambient RF noise floor. This means that UWB

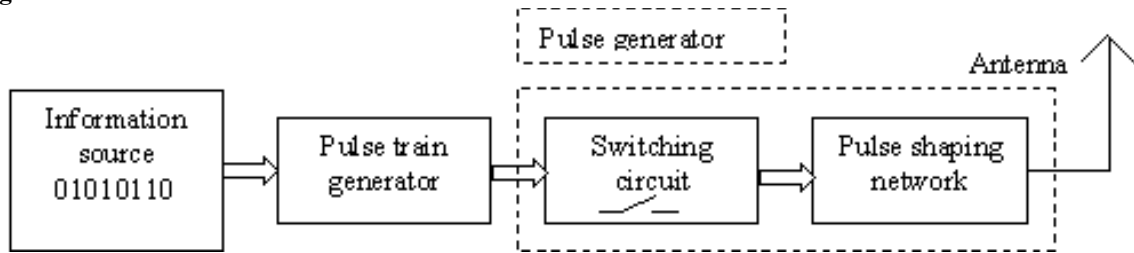


Figure 5: UWB transmitter

Due to its short duration, the spectrum of such pulses is very wide so it can propagate through walls and other obstacles. Because only part of the spectrum is attenuated in any specific medium, the remaining part can propagate without noticeable attenuation. This makes it relatively immune to fading problems.

The other, often discussed, advantage of UWB systems for sensor networks is three-dimensional tracking with very accurate results down to a few centimetres, especially in difficult indoor environments. This is due to the inherent nature of

does not cause harmful interference with narrowband systems and it is extremely hard to eavesdrop, increasing security.

- The very low UWB signal power levels mean that a UWB based transceiver consumes much less power than conventional transceivers, reducing node power consumption and prolonging battery life.
- If required, UWB systems are able to provide high data rates, potentially up to 500MBps. However, for such data rates, special, extremely accurate clocking is required.

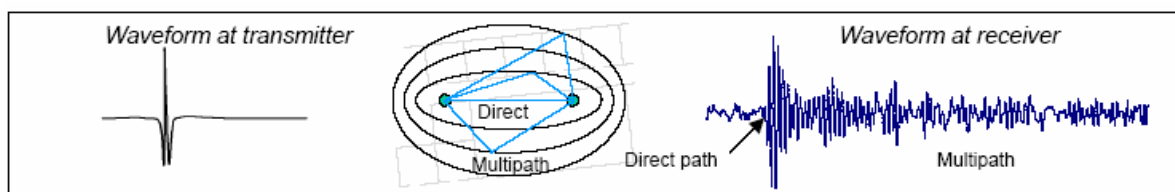


Figure 5: UWB direct and multipath discrimination

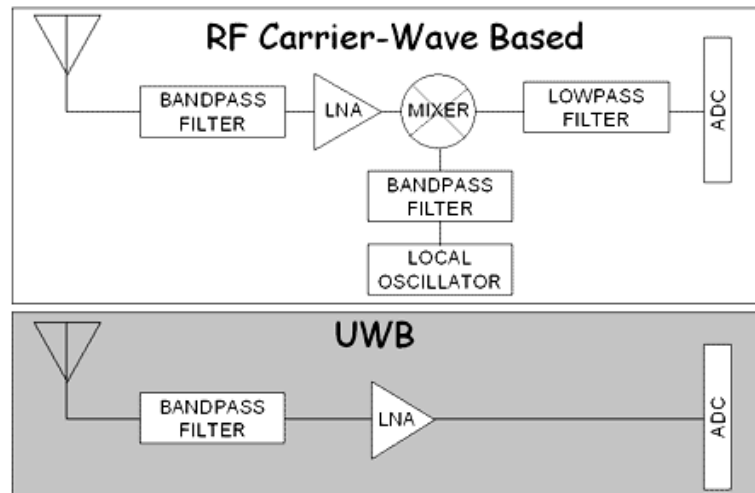


Figure 6: UWB receiver architecture compared to that of a conventional receive

- There are, of course, challenges:
- A block diagram of a UWB transmitter is shown in Figure 6. It is of relatively low complexity but, because of the high frequencies (up to 20GHz), wide bandwidths (up to 500MHz or more) and very short pulse durations it presents very interesting problems in high frequency design. Antenna design is also difficult because of the wide bandwidth. (On the other hand, the low complexity and high frequencies lend themselves to miniaturisation).
- A block diagram of a UWB receiver is shown in Figure 6 in comparison to a typical carrier based RF receiver. The reduction in component count is obvious but the design of them is considerably more challenging demanding electronics which can deal not only with high frequencies and a wide bandwidth but also with very high accuracy timing. If positioning is added then timing synchronisation becomes necessary between multiple UWB receivers, further adding to the challenge.

5.2. UWB at CIT

As part of CIT's work in M-Zones we are developing a transceiver suitable for use in a low cost, miniaturised sensor node. At present design effort is focusing on the UWB transmitter. The active part of transmitter is a step recovery diode (SRD) whose special construction permits generation of fast rising pulses. The first version of pulse transmitter contains balanced SRDs with a pulse shaping network at the output. The circuit is able to provide a truly balanced UWB pulse with the following parameters:

- Fall/rise time : 168 ps
- Pulse width : 335 ps (50%-50%)

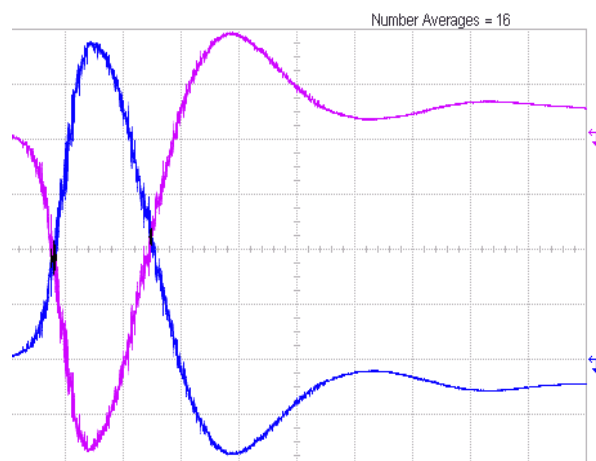
- Pulse amplitude: +/-560 mV

We have extended this circuit to enable pulse phase modulation, amplitude modulation and pulse power control.

Further research is focusing on design a more compact solution for filtered pulses which matches to FCC rulings for UWB communication and projected European rulings. At present work is carrying on design of compact filter and its utilisation in UWB pulse shaping networks. The next step will be the first design of a simple receiver working on the principle of pulse integration.

6. Conclusions

Wireless sensor network hardware involves the integration of many different fields of electronics design with the additional complications of needing to minimise size and power consumption. At CIT we are working on both conventional sensor nodes and on development of sensor nodes based on UWB technology. In M-Zones we plan to demonstrate the use of the nodes in a smart space



context.

The work on sensor nodes is a component of the integrated research objective of the CIT Adaptive Wireless System Group to develop the hardware, operating system and protocols for a mobile sensor network platform.

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