Wireless Data Transmission through Concrete Structures

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Abstract

Chloride ion presence in the concrete pore solution is an important factor in the initiation of rebar corrosion. Therefore, elevated chloride concentration in the pore solution needs to be detected as early as possible. For this early detection to be achieved, it is ideal to deploy sensors inside the concrete structure itself. This allows real time sampling of the pore solution which is closest to the rebar. To achieve this one needs to have a system based on wireless communication which allow the sensors to communicate within the structure. This would avoid wired communications methods, which impart fragility and implementation difficulties.
This literature review paper endeavours to look at the various types of radiation which can be harnessed to penetrate through the opaque concrete structure. Potential data transmission methods utilising Radio Frequency Radiation, Ultrasonic Radiation, X-Ray Radiation and Neutron Beam Radiation physics were reviewed and evaluated against a set of parameters. The paper scores each radiation type against System Size, Power Supply Requirements, Transmission Range, Complexity of Circuits and Safety issues. Through these scores, each transmission technology was graded on its potential to act as the basis on which to build a micrometre sized intra-concrete data transmission system. The paper shows that ultrasonic radiation is the most promising radiation technology for use in this application.

Keywords: concrete; data; networks; microscale; radio frequencies; ultrasonic; X-Ray; Neutron beam; wireless networks.

Introduction

Rebar corrosion is a factor which causes expansion of the steel which in turn causes the concrete structure to crack and deteriorate. Such rebar corrosion is caused by various factors among which is the chloride ion attack of the passivation layer. Chloride ions penetrate into the concrete pores through the pore solution (Wan, Wittmann, Zhao, & Fan, 2013) (Neville, 1995) (Mehta & Monteiro, 2006). If chloride ion concentration is to be monitored close to the rebar, it is important to position the sensory systems on the inside of the concrete structure, where they can directly sample the pore solution touching the rebar (Nokken & Hooton, 2008) (Sammut, Gatt, & Borg, Microscale miniaturisation of chloride ion detection sensors for long-term embedding in reinforced concrete structures., 2021) (Sammut, Gatt, & Borg, Chloride ion detection in concrete through Galvanic and Resistivity methods, 2017). An embedded sensory system would enable real time detection of chloride ions in the pore solution which would permit timely corrective action to be taken on

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the structure. Ideally such sensory systems would be miniature, low cost, and durable Integrated Circuit (IC) sized devices. Such would enable widespread deployment of systems inside many of the concrete structures being built around the world.

Designing systems which need to be positioned in the corrosive environment of the pore solution presents several technical challenges especially the data transmission aspect. Since the sensory system would be widely distributed throughout the structure, the sensors need to have a data connection to the outside world through which they can export their readings. The data communication philosophy could be either to take a direct path where each sensor connects directly to the central node or else by the sensors communicating with each other until the signal arrives to the central node positioned at the surface of the structure. Such a distributed sensor system is shown in **Fig. 1**.

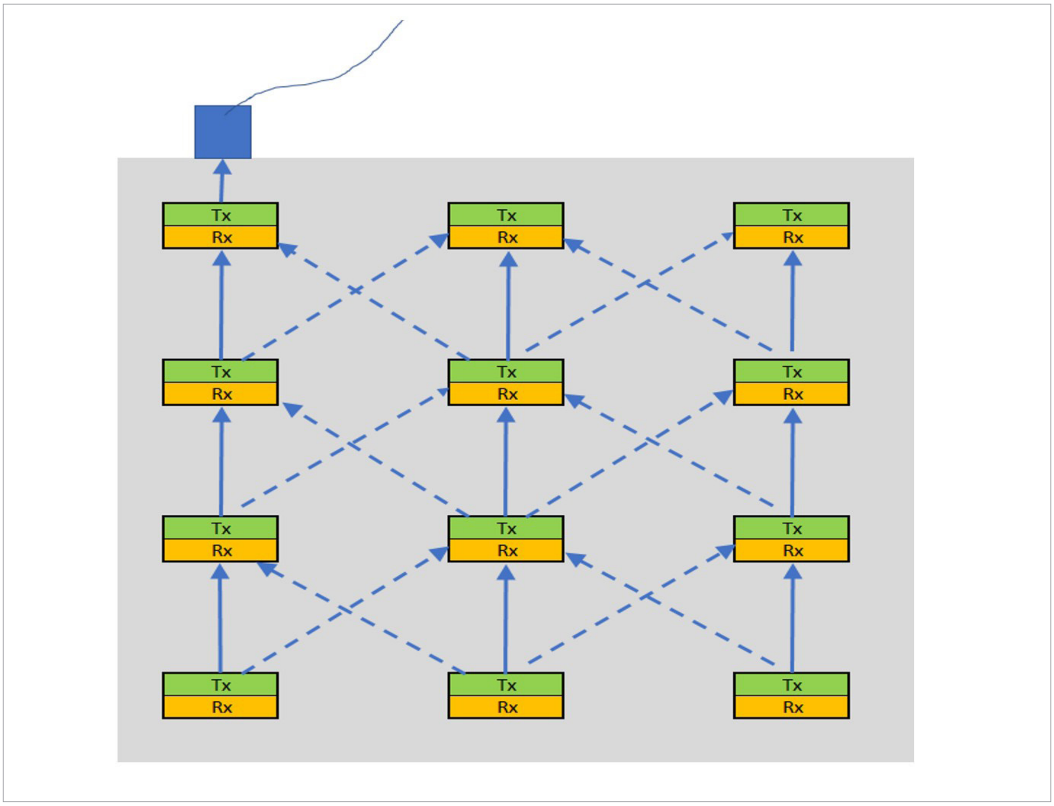


Fig. 1

A conceptual distributed sensory system inside a reinforced concrete structure (Sammut, Development of a Piezoelectric Micromachined Ultrasonic Transducer Optimised to Operate in the Pore Solution of Reinforced Concrete Structures., 2023)

It is not desirable to use wired connections to link the sensors with the central node which is in turn connected to the data processing units. Wired systems have inherent weakness in their connectivity especially when the network is setup by inexperienced construction workers during the construction process. It was therefore for this reason that this paper looked at the feasibility of wireless sensory technology as the selected means of communication.

The figure shows the micro sensors which are presented as the rectangular shapes. These micro sensors are embedded within the Reinforced Concrete structure which is shown in grey. Each of the embedded micro sensors has a receiving (RX) component which is seen shaded in yellow and a transmitting (TX) component which is shown in green colour. The micro sensors will communicate with each other through the receiving and transmitting components with the transmission paths being in the direction of the arrows. The solid arrows show the default communication path while the dotted arrows show the alternative paths which are utilised by the sensors to achieve a redundant system. As can be seen in the figure, the distributed sensors were only envisaged to transmit data in one direction, towards the surface of the reinforced concrete. This means that the receiving components of the sensory system always work as receiving components while the transmitting components only work in transmission mode. Thus each of the components can be designed specifically for its specialised role, transmission or reception, and optimised accordingly.

At the surface, a detector (shown as blue box) picks up the signals which it then transmits onward out of the system for analysis. The analysis conducted on this data allows the determination of the structural interventions which may be necessary to counter the Structural Health Monitoring situation being detected.

The scope of this paper was to provide a review of available literature focusing on wireless data transmission technologies. Through this extensive review, the ideal method of data transmission which can be utilised in the design of the micro sensors' data transmission system can be deduced.

Use of Radio Frequency (RF) Radiation Physics

Reinforced Concrete is a complex material which can attenuate and reflect radio waves. Systems must therefore be carefully designed to ensure that they can always successfully transmit data correctly, when embedded in the concrete structure (Chiba & Miyazaki, Dependence of Radio Wave Reflection and Transmission Characteristics of Reinforced Concrete Slabs on Frequency and Angle of Incidence, 2002).

The RF spectrum is subdivided into multiple frequency bands. Two of the frequency bands which will be looked at in this section are the Very High Frequency (VHF) and the Ultra High Frequency (UHF) bands. The very high frequency VHF band is in the range between 30 MHz to 300 MHz while the Ultra High Frequency band is between 300 MHz and 3 GHz (Holker, 1993). Reviewed literature studying radio frequency propagating through solids indicated that high density solids or water content inside a solid's pores have the effect of absorbing and attenuating the signals (Zhou, Sheng, Deng, Wu, & Fu, 2017). Such absorption has a heating effect on the concrete. This occurs through a process in which RF radiation is absorbed by the concrete with the RF energy being converted into heat by the structure. In fact, in production environments radio waves are used to heat up concrete in order to accelerate the curing process (Hohlig & al, 2017).

RF radiation is also used in the study of concrete structures. A reviewed paper described techniques which utilised ultra-wide band radio frequencies through which to conduct material internal composition inspections. This paper mentioned the challenges faced when using RF equipment to conduct analysis on concrete samples. The frequencies used to conduct these inspections were between 30 and 970 MHz. In the procedure conducted to prepare the samples for the RF analysis, the samples were dried for 30 days before the procedure was carried out. The study of the internal composition was conducted by studying the deflection of the incident radio waves (Blanco-Murillo & al, 2017).

Another reviewed paper discussed the use of radio waves in high frequency ground penetrating radar through which to study the subsurface. The frequencies used were between 450 MHz and 900 MHz and the signal penetration into the ground was measured to be around 2m. The system used in this case required an external power source and was a large wheeled piece of equipment (Cassidy, Eddies, & Dods, 2011).

Through the literature review it was evident that past research focusing on the transmission of radio waves through structures had been conducted. This past research was conducted due to the need for use of mobile telephony indoors and hence the importance of signals to propagate through walls (Chiba & Miyazaki, Dependence of Radio Wave Reflection and Transmission Characteristics of Reinforced Concrete Slabs on Frequency and Angle of Incidence, 2002). Apart from the absorption of radiation by the concrete material as discussed before, it is important to note that in reinforced concrete structures the steel reinforcement itself also has an effect on the signal. In fact at low frequencies the rebar structure is the most important attenuator of the RF signal while as the frequency increases the concrete itself starts to have a more important attenuative effect. As an example one could expect a 10 dB attenuation increasing to 20-30 dB if one factors in signal to noise ratio, with a wall thickness of around 0.2 m. This reviewed paper again concludes and confirms that RF signals suffer sever degradation during transmission through RC structures (Dalke, Holloway, McKenna, Johansson, & Ali, 2000).

With regard to the rebar, the diameter and the pitch of the rebar also has a strong effect on the transmission of RF radiation. Calculated results reviewed in literature, have indicated that the transmittivity of concrete was found to vary from 0.84 for a sample with a rebar diameter of 0.002 m and pitch of 0.02 m to a transmittivity of 0.01 for a sample with a rebar diameter of $5x10^{-4}$ m and a pitch of 0.0026 m. Experimental values of transmissivity varied between 0.92 and 0.01 for the same pitch and rebar diameters. This reviewed document confirmed, that the reflection and transmission characteristics of concrete is affected by the water content, especially for frequencies between 1 to 100 GHz, which polarise the water molecule (Chiba & Miyazaki, Reflection and Transmission Characteristics of Radio Waves at a Building Site Due to Reinforced Concrete Slabs, 1998). Further reviewed studies again confirmed that the moisture content substantially attenuated the RF radiation. Concrete with the lowest level of moisture caused an attenuation of 6dB at a frequency of 4 GHz while a higher water to cement ratio even attenuated the radiation to about 12 dB at the same frequency (Asp, Hentilä, & Valkama, 2019).

Reviewed systems which use RF communication included technologies such as Bluetooth, Radio Frequency Identification, and Wireless Local Area Network systems (Liu P. , 2014). These will be reviewed in further detail in the subsections below.

Use of Radio Frequency Identification (RFID) technology

There is great interest in basing concrete health monitoring sensors on RFID technology. Such technology offers a cheap, low power consumption platform which can cover a notable transmission distance due to their operation on Ultra-High frequency (UHF) bands with a wide bandwidth (Zhou, Sheng, Deng, Wu, & Fu, 2017).

Such a reviewed system with potential for embedding in concrete, utilised the concept of induction to transfer data and to power the sensory circuitry. It explores the use of a Radio Frequency Identification (RFID) tag as a passive embedded system, which does not require a power source, unless it is in the process of being read. Such identification tags are normally used for the tagging of consumer goods (Materer, Apblett, & Ley, 2011).

In another project which was reviewed, the frequency used for data communication was 915 MHz, with a 50 Ω micro strip antenna being utilised to extend the data transmission range. The antenna was constructed using copper traces with a thickness of 3.5×10^{-6} m. When buried in 0.02 m of concrete, the measured antenna gain was -32 dB and demonstrated an efficiency of 37.2%. Noise was then removed from the received data stream to extract the original data from the signal. In this project wavelet de-noising was employed. The system used was effective in removing all the noise and transmitted data up to a range of 15 m (Zhou, Sheng, Deng, Wu, & Fu, 2017).

In another scenario the RFID system was embedded in a concrete structure where the pore solution acted as an electrolyte in which two different metals, came together to form a galvanic cell. On the initiation of the corrosion process there was an electrical potential generated between the two electrodes (Perveen, Bridges, Bhadra, & Thomson, 2014). This change in potential, was designed to cause a change in the capacitance of a varactor diode's junction capacitance. The change of the junction's capacitance altered an on board sensory coil´s resonant frequency which was detected by an external interrogator coil. Sensor performance declined with increase in the distance between the embedded coil and the reader´s coil. The equivalent potential error increases to 23.08mV at a distance of around 6 cm (Perveen, Bridges, Bhadra, & Thomson, 2014).

Since the system requires each RFID to be read manually it may be of limited use for an autonomous network of sensors. In reviewed literature this system was used as basis for the design of a concrete humidity monitoring system where an RFID was embedded at a depth of eight cm in the concrete. An RFID reader was placed in the air above the concrete directly over the RFID. The two were operating at a resonant frequency of 915 MHz. At this frequency the device managed to achieve a maximum operating distance of 17 m (in free space) with a power dissipation of 5.7 μW. With this frequency the best performance was achieved (Zhou, et al., 2016).

Use of Custom built Radio Transmission Systems.

Commercial RFID devices demonstrate several disadvantages especially when it comes to data stream reliability. Reviewed literature has shown that custom RFID circuits have been designed to overcome these disadvantages. These custom-made designs were usually PCB based which were much larger and more expensive than IC sized devices when mass produced (Materer, Apblett, & Ley, 2011). The prototype custom RFID devices were designed with a number of inbuilt features to make the systems more reliable, and better suited to the application of monitoring concrete structures (Materer, Apblett, & Ley, 2011).

In a reviewed prototype circuit, the current induced in the inductor (RF coil), was rectified with a Graetz bridge composed an N channel MOSFET and two low forward voltage diodes. The filtering was done with a capacitor and regulated by a Zener Diode. A microsystem PIC processor emulated the RFID IC (Em4001) and returned the data (64 bits) which was then transmitted. Parity bits were used in the return data to make the data transmission more reliable.

During this testing it was recorded in the reviewed literature that the capacitor, repetitively failed. It was hence deemed necessary that a high quality, high temperature RF device be utilised instead of the one that was originally selected. The frequency which gave the best results was found to be around 125 kHz (Park, Choi, Kim, & Chung, 2005) (Pereira, Figueira, Salta, & Fonseca, 2008).

Use of Radio Frequency Integrated Circuits

Radio Frequency Integrated Circuits (RFIC) use specialised printed circuit boards which utilise RF technology to provide a wide range of functions including integration with sensors, and providing important monitoring functions (Changa, Hung, & Peng, 2011) (Zirbesegger, Gebhart, Merlin, & Leitgeb, 2007). The system included various interconnecting blocks. The sensory element fed an A/D converter which in turn was connected to a micro control unit controlling the encoder. This in turn controlled an RFIC transmitter which transmitted RF radiation to an RFIC receiver which was set up away from the transmitter. The RFIC receiver was connected to a decoder which was in turn connected to a micro control unit driving the user interface.

RFIC provide a flexible technology platform. In a reviewed project the RFIC receiver was connected to the computer via USB through which it transferred the data receives from a transmitter embedded in the concrete. The system was successful in transmitting a detailed spectrum of temperature readings across time. However, the stability and continuity of the signal transmission from inside the concrete were some of the issues which needed to be improved further.

Use of Low Power RF Transmitters.

Literature review has shown that wide scale research effort in the field of RF transmission has been conducted to develop high performance and low-cost RF integrated circuits (Wann & Wang, 2011). Results reviewed from literature showed that a device, when transmitting at a frequency of 2.4 GHz, provided 15.5 dB of power conversion gain. It drew only 6 mA at a supply voltage of 1.2 V. The size of the IC was around 9×10^{-4} m x 1.1×10^{-3} m (Wann & Wang, 2011).

There are therefore, off the shelf products which already provide system on chip device platforms featuring ultra-low power microcontrollers combined with integrated RF cores. These are used for consumer networking, industrial monitoring, biomedical applications and energy harvesting. The TI CC430 system is one such device which operated at 1 GHz (Instruments, 1998).

Use of Power Utility Frequencies

Alternating current frequencies used by power utilities are normally in the 50 or 60 Hz range (Owen, 1997). A reviewed paper looked at the transmission of power through concrete at a frequency of 60 Hz. Various projects have transferred power using wireless transmission operating at RF frequency, however the paper looks at the use of a utility frequency of 60 Hz to affect the power transfer. To utilize a low 60 Hz frequency a silicon steel magnetic core was used to help achieve an optimal Q factor which was difficult to achieve at low frequencies. Steel structures embedded in the concrete also had a degradation effect on the power transfer. In a 0.1 m thick reinforced concrete wall the energy transfer efficiency was 67.1% (Ishida & Furukawa, 2015).

Use of Microwave Frequencies

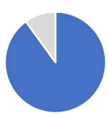
Formally microwave frequencies are recognised as those having wavelengths shorter than 1m (frequencies above 300MHz) however the industry recognizes frequencies above 1 GHz as being in the microwave range (Poole & Darwazeh, 2016). For the purpose of this study the microwave frequency range can therefore be considered as being between 1 GHz and 100 GHz. Some available communication systems operate at these frequencies such as broadcast satellites operating at 12 GHz, and mobile phones at 1 to 3 GHz. Silicon devices are limited to 1.5 GHz and therefore devices operating above this frequency are normally based on GaAs technology (Ohring, 1998).

Microwave frequencies have been found to be used for the analysis of various material parameters such as the moisture content and density. In a reviewed paper, frequencies between 2 and 7 GHz were utilized to measure the dielectric constants from which to derive the density of the concrete (Lee, Phua, Lim, You, & Cheng, 2019). Systems to operate at such frequencies are readily available since these frequencies are used by mobile phones. Another reviewed paper describes the use of frequencies within the 300MHz-30GHz range and describes how frequencies in the lower part of this range penetrate and propagate through concrete. In this paper a pair of antennas operating at a frequency of 2.5 GHz were used to conduct analysis of RF transmission in concrete. A -30 dB coupling was achieved when one of the antennas was buried in concrete at a depth of 0.1 m inside the concrete structure. The losses of a dipole antenna located inside a bridge pier was also investigated and was not found to work effectively. The antennae used were also relatively large in size although the paper also looked at Antipodal Vivaldi Antennas (AVA) which use ultra wide frequency bands and have smaller dimensions than dipole antennas. The paper mentioned an AVA operating at a frequency range of between 0.65-2.6 GHz. It also identifies the fact that rebar acts as a radiation shield for microwave frequencies if the mesh period is less than half the electrical half wavelength (Esmati & Moosazadeh, 2018).

The effect of the rebar on data transmission has been studied by other reviewed authors who also confirmed that this effect is frequency dependent. As an example, a reviewed study has established that when there was no rebar in the concrete, at a frequency of 433 MHz the coupling between transmitting and receiving antennae was 3.77dB better than the coupling achieved at 2.45 GHz. On the other hand, experimentation with two layers of rebar between two patch antennas resulted in a signal reduction of 1.61 dB, due to the rebar effect when the two antennae were coupled at 433 MHz. This negative effect on the coupling of two antennae by the rebar was reduced as the wavelength reduced. The best frequency for coupling between two antennas in reinforced concrete was identified as being 915 MHz (Jiang & Georgakopoulos, 2011).

Table 1 summarises the parametric scores for radio frequency transmission as medium for data transmission.

Table 1. Parametric score for radio frequency data transmission

Parameter	Score	Description
System Size	 6/10 Device size limited by antenna size	Radio frequency devices' sizes are constrained by the size of their antenna which in turn is sized in relation to the operating frequency. As an example, reviewed literature indicated that for a resonant frequency of 1.06 GHz an antenna length of $6x10^{-3}$ m needs to be used. This is needed to adequately match the antenna and obtain the highest transmission efficiency possible (Iftissane, Mamouni, & Zenkouar, 2011). On the other hand, rebar affects the coupling efficiency especially at the higher frequency in the GHz range (Jiang & Georgakopoulos, 2011). The circuitry required to drive the antenna has also been miniaturised with literature describing the availability of an IC driving circuit having a size of around 0.009 m x 0.0011 m (Wann & Wang, 2011). The only antennae which were miniaturised close to microscale viewed in literature were in the high GHz range. A 24 GHz transceiver designed for radar systems had an antenna system set on a footprint having a 1.925cm x 0.525 cm dimension (Ko, Moon, & Kim, 2024). One of the very few real microscale sized antenna which was reviewed in literature had a length of 453 μm and operated at a frequency of around 462.5 GHz (Paudel, Li, & Seet, 2024). Others operated at a carrier frequency of 0.24 THz (Kallfass, et al., 2015) or 1.02 THz (Sen & Jornet, 2019). Due to the antenna to wavelength relationship all of the microscale miniaturisation work reviewed was in the terahertz region (Yi, et al., 2021) (Deepa & Sudha, 2021).
Power supply require-ments	 6/10 Low power transmit-ters developed	Various low power supply solutions for RF transmission have been developed. Low power transmitting circuits described in literature as drawing only 6mA at a supply voltage of 1.2 V have been developed (Wann & Wang, 2011).
Range of transmis-sion	 1/10 Poor transmission range in concrete	While radio frequencies have extremely good transmission capabilities in air, literature tabulating experimental and simulation work conducted has shown that RF radiation has poor transmission range in concrete structures. Rebar also negatively effects the range of transmission (Esmati & Moosazadeh, 2018). Further reviewed work conducted with millimetre wave imaging systems showed an attenuation distance in concrete of 6 mm beyond which the signal was completely attenuated. The frequency utilised was between 76.5 GHz and 81 GHz. It is also important to note that the antenna unit used had the dimensions of 52.5 mm x 73.6 mm x 19.4 mm (Murakami & Fukuda, 2024).
Complexity of circuits	 5/10 Very high frequency circuitry is required	Due to the antenna design considerations discussed above, miniaturisation of the antenna requires increasing the frequency of transmission. Reducing the antenna sizes to the microscale results in having to use resonant frequencies in the high GHz range (Iftissane, Mamouni, & Zenkouar, 2011). These very high frequencies cause the driving circuitry to become much more complex including the need for extensive designs required to impart noise immunity.
Safety issues	 9/10 Safe to biological matter	The transmitting power levels used in this project would be at very low power levels. Systems with frequencies operating at 3, 10 or 28 GHz (for 5G) are widely used in applications such as mobile telecommunications. This means that they have been extensively studied from a human safety perspective through studies conducted such as dosimetry. One particular cause of concern which was studied, was the heating effect which high frequency RF may have on biological matter especially when such matter is situated near to the antenna. This is especially relevant when the frequency being used is in the microwave range. Literature has indicated that heating effects on biological matter only occurred when the body was near to the antenna and the exposure lasted at least several seconds. In the case of this proposed project the antenna would be embedded in concrete and therefore it would not be possible for a biological body to be very close to it during transmission (Hirata, Funahashi, & Kodera, 2019).

Use of Ultrasonic Radiation Physics

Ultrasonic radiation is already utilized extensively to carry out studies on the structure and interior of concrete constructions. In non-destructive testing processes, defects within the concrete structure are actually examined through the use of ultrasonic radiation. Such examination involves the transmission of ultrasonic waves into the concrete structure with analysis of the reflected waves being conducted via electronic detection mechanisms. Concrete is not a homogenous medium, with its internal structure contains voids and aggregate of various sizes interspaced throughout it. This causes any ultrasonic waves travelling through the concrete to experience a scattering effect. The scattering effect follows the function a/γ where "γ" is the wavelength and "a" is the characteristic length. The depth of penetration of ultrasonic radiation depends on its frequency. As the frequency decreases, the penetration depth increases (Seher, Chi-Won, & Kim, 2013).

The type and composition of the concrete influences its ultrasonic attenuation coefficient. As an example, literature outlined that concrete with a water/cement ratio of 0.45 had an attenuation coefficient of 7.2176 dB/m, while an attenuation of 8.1914 dB/m was observed in concrete with water/cement ration of 0.4. The attenuation coefficient was also affected by the mix design especially the proportion of fine aggregate to coarse aggregate. For example, concrete with a 30:15 weight proportion of coarse to fine aggregate had an attenuation coefficient of 7.2d B/m while concrete with a 40:55 ratio had an attenuation coefficient of 16.6 dB/m. The ultrasonic vibrations in the concrete structure were detected through a laser Doppler vibrometer (Abdullah & Sichani, 2009).

As discussed, concrete is not a homogenous medium and does not demonstrate properties which are completely linearly elastic. The heterogeneous concrete structure means that ultrasonic radiation travelling through the concrete is subject to reflections and scattering as well as attenuation by the internal geometry and structure inside the concrete. The velocity and amplitude of the ultrasonic radiation is affected by factors such as the type of concrete, the compressive strength, moisture and concrete degradation. Literature has described the propagation of ultrasonic radiation through the concrete through both shear and compression waves (Niederleithinger, Wolf, Mielentz, Wiggenhauser, & Pirskawetz, Embedded Ultrasonic Transducers for Active and Passive Concrete Monitoring, 2015).

The velocities of the compression c_p and shear waves c_s in a linear homogenous elastic material are given by Equation 1 and Equation 2 (Niederleithinger, Wolf, Mielentz, Wiggenhauser, & Pirskawetz, Embedded Ultrasonic Transducers for Active and Passive Concrete Monitoring, 2015).

$$c_p = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}} \quad (1)$$

$$c_s = \sqrt{\frac{G}{\rho}} \quad (2)$$

Where: E is the Young's Modulus, v is the poisson's ratio, G is the shear modulus, ρ is the density

If ultrasonic radiation is to be used effectively for data transmission purposes, the changes in attenuation coefficients need to be studied further. The frequencies used in the identification of concrete damage are normally lower than 100 kHz which ensures that the interactions of small wavelength waves and the scattering effect of aggregate on ultrasonic radiation is avoided (Mustapha, Lu, Li, & Ye, 2014).

Ultrasonic transmission mechanisms have also been used to transmit data through water. Silicon/PZT laminate actuators have been designed to act as transducers and be used for underwater digital data transmission. Coded binary data can be transmitted through ultrasonic means by using two frequencies which alternate (Siwapornsathain & Lal, 2001).

Another reviewed paper described a prototype system which was capable of data transmission through steel plate up to 0.063 m thick. Data transmission through the steel plate was managed at a speed of 17 Mbps and the system was also capable of transmitting electrical power at fifty watts. For power transmission the frequency used by the piezo transmitter was 1 MHz while for the data communications, 4 MHz was used (Lawry, Wilt, Ashdown, Scarton, & Saulnier, 2013).

Solids forming structures such as pipes or cylinders have also been used as channels for communication. In a reviewed system, plates and pipes up to 1.94 m long were used. Instead of a piezoelectric transducer an Electromagnetic Acoustic Transducer (EMAT) was used. EMAT devices can work in hostile environments such as high temperatures however these require higher excitation power than comparable PZT. Communications passing through solid structures are negatively affected by mechanisms such as wave refraction, scattering, absorption and dispersion. The system used 125 MHz for the data transmission to achieve data transmission rates of 40kbps and 20kbps in the plates and pipes respectively (Saniie, Wang, & Huang, 2018).

Another reviewed paper examined ultrasonic transmission in steel plates immersed in water. Ultrasonic energy was transmitted through a $6x10^{-3}$ m thick stainless-steel plate mounted inside a full water tank. A distance of 0.127 m from transmitter to steel plate and 0.065 m from the steel plate to the receiving hydrophone was set. It was determined that when the incident angle was changed, the resulting transmitted wave was affected. Rayleigh-Lamb waves were generated in the fluid on both sides of the plate, thereby attenuating the propagation of the guided waves being transmitted through the plate. Maximum transmission efficiency occurred at a transmitting frequency of 482 kHz when radiation was intersecting the plate at normal incidence. The frequency is related to the resonance at half wavelength in the plate (Lohne, Vestrheim, & Lunde, 27-30 January 2008).

One of the reviewed papers, studied guided ultrasonic wave propagation, through pipes embedded in concrete. In this case the ultrasonic radiation was used for the routine inspection of pipework using low frequency ultrasonic waves having a frequency which was below the 100 kHz threshold. Guided wave testing sensors pick up the propagated radiation. Normally in exposed above ground bare pipe configurations ultrasonic radiation propagation covers ranges of tens of meters. The pipes themselves basically act as a waveguide which effectively channels the ultrasonic radiation. However, in buried pipes the range travelled by the ultrasonic radiation decreased significantly due to the guided waves being attenuated by the coating or material surrounding the pipe. The reviewed paper outlines the fact that different concrete types have different acoustic properties (EliLeinov, S.Lowe, & PeterCawley, 2016). As an example, ultrasonic radiation travels at a longitudinal velocity of 2,810 m/s in grout with a density of 1,600 kg/m^3 while in concrete with a density of 2,300 kg/m^3 the same radiation has a longitudinal velocity of 4,222 m/s. Steel with a density of 7,932 kg/m^3 is much denser than concrete which has a density in the range of 2,320 kg/m^3 for concrete (depending on parameters such as cement/water ratio) (Building code requirements for structural concrete and commentary, 2008). Simulations were carried out on a 0.2 m diameter pipe using a frequency range between 19 and 35 kHz with calculations of the ultrasonic radiation's parameters being carried out at various points on the 4 m long pipe. Results from the work conducted showed that when the pipe was fully embedded in concrete the transmission losses were around 20 dB at an operational frequency of around 30 kHz. On the other hand the transmission losses decreased to less than 10 dB in pipes which were half encased by concrete at the same 30 kHz operating frequency (EliLeinov, S.Lowe, & PeterCawley, 2016).

Ultrasonic waves are also used to detect corrosion in rebar by studying the dispersion curves when using a 40 kHz signal. Experiments were conducted with rebar having 0.02 m diameter through which various studies were conducted in the propagation of ultrasonic radiation through the steel. This determined that corrosion causes a variation in the ultrasonic radiation peak value (Li, Zhang, Yang, & Zhang, 2014).

Ultrasonic methods used for structural health monitoring were also used to monitor the condition of steel rope structures which are used in the reinforcement of overhead power transmission lines. For this monitoring system the actuators and sensors used to conduct the structural health monitoring were built from piezo electric material. These were attached along the length of the steel cables being monitored. Any discontinuities in the cable cause the incident ultrasonic waves to be subjected to mode conversion, and scattering. These principles are used to detect mechanical faults in the steel cables (Gaul, Sprenger, Schaal, & Bischoff, 2012). While such mechanisms would be useful for being harnessed to form the basis of fault detection mechanisms, they could potentially disrupt communication mechanisms if the steel reinforcement is used as communication media. The reason being that discontinuity on the reinforcement can potentially reflect part of the incident waves through which the communication is occurring.

Wave energy propagating in rebar surrounded by concrete, can leak into the concrete itself through S and L waves (BN., 1998). Reviewed literature has indicated that with an increase in frequency the ultrasonic energy tends to get concentrated towards the centre of the rebar. The velocity of the ultrasonic radiation reaches the velocity reached by L waves in steel and hence the leakage of radiation into the concrete decreases. A reviewed project used a 2 MHz frequency to transmit ultrasonic radiation. This high frequency was used to detect deformation of steel bar surrounded by mortar (MD, MJS, & P., 2003). Another reviewed project utilised a frequency of 5.08 MHz. However this high frequency caused insensitivity to defects and therefore was not successful in its scope to be useful in the conduct of NDT (Ervin & Reis, 2008).

Technology required for the manufacture of ultrasonic transducers is nowadays becoming more widely available. Micromachined ultrasonic transducers are being developed to cater for various uses. These are either based on piezoelectric processes or capacitive processes. The former category is known as Piezoelectric Micromachined Ultrasonic Transducers (PMUT) while the latter category is known as Capacitive Micromachined Ultrasonic Transducer (CMUT) (Sammut, Gatt, & Borg, Design of the data transmission component of a micrometre scale chloride ion sensor embedded inside a concrete structure, 2021). The reviewed project used processes based on the use of piezoelectric materials such as Aluminium Nitride.

Arrays of Piezoelectric Micromachined Ultrasonic Transducers, with the active part having 40-micron radii or less have been developed for various applications, mostly using air as medium. Some of the research papers also looked towards using liquids as coupling fluids. Examples which were reviewed in literature indicated that such arrays, when immersed in water, gave an output pressure of around 20 kPa (Shin, et al., 2020). PMUTs developed for other projects which were reviewed demonstrated different acoustic pressures in water where one project reported pressures of 6kPa (Wang, Zhou, & Randles, 2016), another 1 kPa (Liu, et al., 2019) and a final one 15 kPa (Jiang, et al., 2017). Work has also been undertaken in the design of PMUTs which can operate around and below the 100 kHz range when deployed in liquids. Operating in liquids is an essential prerequisite for being able to be deployed in concrete since liquids rather than gases are needed to act as an effective coupling fluid between the PMUT and the concrete medium. Laboratory work using laser vibrometry as well as hydrophones/ultrasonic projectors, has indicated that effective transducers can be built and operated at this frequency range of 100 kHz and below. This frequency level enables optimal ultrasonic transmission inside the concrete structure (Sammut, Gatt, & Borg, Low frequency Piezoelectric Micromachined Ultrasonic Transducers optimized for concrete structures, 2023).

Literature has also shown that embedded ultrasonic transducers are able to survive their integration in the concrete structure for several years. An example showed that sensors embedded in the concrete of a dam in Saxony Germany, had survived a 35 year period of embedding after which they successfully operated (Niederleithinger, Wolf, Mielentz, Wiggenhauser, & Pirskawetz, Embedded Ultrasonic Transducers for Active and Passive Concrete Monitoring, 2015). Table 2 summarises the parametric score for data transmission systems based on ultrasonic radiation physics.

Table 2

Parametric score for ultrasonic radiation data transmission

Parameter	Score	Description
Sytem Size	 10/10 Technology for miniaturised to the microscale is available	Transducers with an active part having a diameter of 0.02 m and a length of 0.035 m have been developed (Niederleithinger, Wolf, Mielentz, Wiggenhauser, & Pirskawetz, Embedded Ultrasonic Transducers for Active and Passive Concrete Monitoring., 2015). Technology which can be used to miniaturise ultrasonic emitters to the microscale is available in the form of ready to use MEMS foundry processes.
Power supply requirements	 7/10 PMUT devices have low energy requirements	PMUTS with reduced power consumption needs are being constantly developed (Qiu, et al., 2015) (Nazemi, et al., 2020). The use of PMUT technology enables lower voltages to be used than what would be needed for comparable CMUTs. This means that power and voltage requirements are further reduced.
Range of transmission	 5/10 Transmission distance of 3 meters indicated	Ultrasonic transmitters which can be embedded into concrete have been developed and operate at around 62kHz. (Niederleithinger, Wolf, Mielentz, Wiggenhauser, & Pirskawetz, Embedded Ultrasonic Transducers for Active and Passive Concrete Monitoring., 2015). Literature has indicated the development of small sized (not microscale) transducers with a transmission range of at least 3 meters in concrete (Niederleithinger, Wolf, Mielentz, Wiggenhauser, & Pirskawetz, Embedded Ultrasonic Transducers for Active and Passive Concrete Monitoring, 2015).
Complexity of circuits	 7/10 Circuits are complex but can be integrated in a semiconductor device.	Circuits to drive ultrasonic transducers are complex as they need to include high voltage power circuits, pulsers, reference clocks, and microcontrollers (Svilainis, Chaziachmetovas, & Dumbrava, 2015). These are quite complex circuits however microcircuits have been developed to do the task. These can be integrated with the PMUT MEMS die in a System in Package (SIP) device (Degertekin, 2017).
Safety issues	 10/10 Low intensity ultrasonic radiation is safe for biological organisms.	The ultrasonic radiation produced by PMUTs which are driven using low voltage is of low intensity (Dubinsky, 2020). Ultrasonic radiation is non ionising radiation and therefore considered much safer than other radiation types such as x-rays. Even high power sonars such as those used in the sea are considered safe when a person is 1m or more away from the source (Kessel, Hamm, & Myers, 2017). This would be the case in this application.

Use of X-Ray Radiation Physics

Hard x-ray sources which generate radiation through the use of portable linear accelerator technologies are used in the non-destructive testing of concrete structures. These use high voltages such as 500 keV to drive the accelerator (Seki, et al., 2017). It is a fact that concrete absorbs x-ray radiation readily and therefore the transmittance of x-rays through concrete having a density of around 2,350 kg/m^3 is poor. With a tube potential set at 150 kV, transmittance in the range of 10^{-5} occurred at a range of 0.30 m. These studies were carried out using Monte Carlo simulations (Noto, Koshida, Iida, & Fukuda, 2009). X-ray sources have been miniaturised for use in space exploration where a 100 keV source has been miniaturised to weigh around 0.160 kg (NASA).

Table 3 summarises the parametric score for data transmission systems based on x-ray radiation physics.

Table 3

Parametric score for x-ray data transmission

Parameter	Score	Description
Sytem Size	 1/10 Relatively large size	Small size x-ray sources have been developed for use in the medical field. Typically sources even the smallest ones weigh more than 0.1 kg (Zhamova, 2016)
Power supply requirements	 1/10 High energy requirements	X-ray sources require high voltages to operate. Even micro focal x-ray tubes require voltages between 30 and 150 kV with nominal power requirements between 0.6 and 5 Watts (Zhamova, 2016).
Range of transmission	 5/10 Short propagation range.	Ordinary concrete is an effective absorber of x-ray radiation and is used to build x-ray shielding. Literature showed that when using a 0.662 MeV x-ray source the transmission level fell below 1%. In this case the x-rays were transmitted through a 0.40 m thick ordinary concrete slab (Stankovica, Ilic, Jankovicb, Bojovic, & Loncar, 2010).
Complexity of circuits	 1/10 Highly Complex	X-ray sources are complex pieces of equipment. Components need to be positioned at exact points to ensure adequate focus. The system needs to have vacuum chambers, and targets incorporated while the detector receiving the radiation is also a complex piece of machinery in its own right (Ebensperger, Stahlhut, Nachtrab, & Hankea, 2012).
Safety issues	0/10 Very Dangerous to biological organisms.	X-rays cause health problems to exposed biological organisms. Apart from the actual safety issues one also needs to factor in the perception of public. In surveys reviewed in literature, the vast majority, more than 90% of respondents, indicated that they believe that x-ray radiation causes health problems (Naqvi, Tahira, Warda, Hasan, & Kinaan, 2019).

Use of Neutron Beam Radiation Physics

The reviewed literature in this area indicated the use of fast neutron beams to build transmission images of the concrete structures (Seki, et al., 2017). Neutron beams are used in structural health monitoring to conduct radiographical studies on structures such as to study absorption or migration of water into concrete. Neutron beam radiography is extremely sensitive to water content in the concrete and therefore useful to detect such moisture. The neutrons which pass through the structure without being absorbed or scattered are detected by a scintillator which plots a radiograph (Zhang, Wittmann, Zhao, Lehmann, & Vontobelc, 2011).

Compact neutron sources have been designed which operate based on an RF ion source which targets tungsten to produce photons and finally a beryllium target to generate the fast neutrons. The compact linear accelerator has a length of around 0.3 m and uses energy in the range of 5 to 10 MeV (Murata, Ikeda, & Hayashizaki, 2017). Research is being conducted to miniaturize neutron beam sources which are not based on nuclear fission to produce their neutrons (Letourneau & al, 2017). The size of neutron sources is being reduced however, operational systems still have sizes of tens of centimetres. This technology is therefore far from the micron size required (Wang, et al., 2014).

Table 4 summarises the parametric score for data transmission systems based on neutron radiation physics.

Table 4

Parametric scores for neutron beam data transmission

Parameter	Score	Description
System Size	1/10 Relatively large size	Neutron sources are relatively large. Compact neutron beam sources are being studied for use to conduct material studies. However, the beam including the ion source is complex with magnets requirements for vacuum and an ion source (Dasa & Shyam, 2009).
Power supply requirements	1/10 High energy requirements	Neutron sources require complex power sources and high energy requirements. Voltage amplitudes of up to 450 kV are used as well as power supplies capable of providing an operational current of 1.5 kA (Vovchenko, Isaev, Kozlovskij, Shikanov, & Shkolnikov, 2017).
Transmission range	7/10 Good propagation range	Studies conducted to design shielding for neutron beams have established that measurable levels with a dose equivalent of 1.68×10^{-16} rem/(n/cm^2) were measured at a depth of 6.515 m. This was measured using 75MeV in the source (R.W.Roussin, Alsmiller, & Barish, 1972).
Complexity of circuits	1/10 Highly Complex	Circuits for neutron sources are highly complex with multiple transformer stages being integrated together (Vovchenko, Isaev, Kozlovskij, Shikanov, & Shkolnikov, 2017).
Safety issues	1/10 Dangerous to Health	High energy neutron sources are a danger to Health and Safety. These increase the risk of carcinogenesis (Bezak, Takam, Yeoh, & Marcu, 2017).

Analysis of Results

For ease of assessment the results achieved by each of the technologies is summarised in this section. The summary of all the scores is shown in Table 5. This table gives the reader the opportunity to review and compare the capabilities of every technology with comparative scoring in each of the five reviewed fields.

Table 5

Summary from literature review of data transmission mechanisms

Type of Radiation	System Size	Power Supply Requirements	Transmission Range	Complexity of Circuits	Safety Issues
Radio Frequency Radiation	6/10	6/10	1/10	5/10	9/10
Ultrasonic Radiation	10/10	7/10	5/10	7/10	10/10
X-Ray Radiation	1/10	1/10	5/10	1/10	0/10
Neutron Beam Radiation	1/10	1/10	7/10	1/10	1/10

As can be seen in the table, ultrasonic radiation consistently scored highest in all the reviewed areas, namely system size, power supply requirements, transmission range, complexity of circuits, and safety issues. Radio Frequency Radiation scored less than Ultrasonic Radiation in all areas. However, it was considered as having achieved second place and therefore can also be considered further. On the other hand x-ray radiation and neutron beam radiation received unacceptably low scores in most categories. This means that they are of no use for this application.

Conclusions from the Reviewed Literature

This paper identifies ultrasonic radiation, as being the technology which achieved consistently high scores in each of the reviewed parameters. This technology therefore promises to be a highly effective method for data transmission within solid structures such as concrete. Utilising an ultrasonic transmission path provides a number of advantages to an eventual sensory system, particularly if Piezoelectric Micromachined Ultrasonic Transducers (PMUTs) are used.

The most important parameter outlined by this review was the effectiveness of the transmission path. This is the most important parameter from those reviewed, as without the possibility of having a viable transmission path there would be no scope for further consideration of that particular technology. Through the reviewed literature it could be deduced that the use of an ultrasonic transmission channel would allow for an effective data transmission path even through dense materials. However other technologies can equal or even exceed the transmission range of ultrasonic transmission in such media. Therefore, before deciding on the final technology on which to base an eventual system, other parameters needed to be reviewed.

Two such parameters were, the system size and the complexity of the electronic circuits which are required. A good score in these two parameters enable the development of technologies that are durable, reliable, and less susceptible to physical damage and degradation over time. This ensures the long-term reliability of the data transmission system. Good results in these parameters was certainly not the case for transmission methods using neutron beam or x-ray technologies. In these cases literature has indicated that equipment needed to produce and detect this radiation would be complex. Miniaturisation for these two technologies is therefore only possible to an extent and certainly not to microscale levels with current levels of technology.

Radio Frequency physics scored in second place behind ultrasonic radiation, in the areas of size and circuit complexity. An important issue which precludes the miniaturisation of Radio Frequency based systems to microscale size, is the fact that the antenna needed to have a size which is related to the wavelength of the signal being transmitted. Therefore microscale antennae can only be useful for the GHz and THz, RF regions where the wavelength is very short. Such high frequency transmission has a very limited range high density media such as concrete and therefore of limited value for such an application. On the other hand PMUTs which would have device diameters at 700 to 1,000 µm would be capable of resonating at and around the 100 kHz mark and this would be ideal for this application (Sammut, Gatt, & Borg, Low frequency Piezoelectric Micromachined Ultrasonic Transducers optimized for concrete structures., 2023).

The power supply requirement is another essential parameter. X-ray, and neutron beam technologies both require significant power supply requirements which takes them out of the reckoning for a system which needs to be deployed inside a structure over a significant number of years. Systems based on RF as well as those based on ultrasonic transmission physics on the other hand, have less onerous power supply requirements. This is true both in terms of the system overall power requirements as well as the voltage levels required. The latter parameter is important, as high voltage systems are much more complex to be developed on a microchip. For ultrasonic radiation based systems, it would be better to use PMUT rather than CMUT technology. The reason being that PMUTs need lower voltages to operate rather than CMUTs which require a substantial DC bias voltage level. Moreover, ultrasonic transducers also have the possibility of being able to conduct energy scavenging to supplement energy sources and provide for energy needs which may span a number of years. Such scavenging can also utilise background vibration which is travelling through the structure. This allows the energy source to last indefinitely (Sammut, Development of a Piezoelectric Micromachined Ultrasonic Transducer Optimised to Operate in the Pore Solution of Reinforced Concrete Structures., 2023) (Birjis, Swaminathan, Nazemi, Raj, & Munirathinam, 2022).

Finally, and not to be underestimated, is the safety aspect parameter. X-ray and neutron beam technologies both produce radiation which is harmful to biological life which therefore precludes their use in most structures where interaction with biological life is possible. Ultrasonic radiation, particularly when operating at the low power levels required for this application, is completely safe to biological lifeforms. This technology can therefore be easily integrated into all structures, including residential buildings that are in close proximity to biological life.

In view of this comparative assessment, based on the comprehensive literature reviewed, this paper concludes that the development of an intra-concrete transmission system should prioritize the use of ultrasonic radiation as the fundamental physical principle. It is also important to note that the development of this technology would not only be useful for chloride ion detection systems, but also for the development of other Structural Health Monitoring systems.

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References

Abdullah, A., & Sichani, E. F. (2009). Experimental study of attenuation coefficient of ultrasonic waves in concrete and plaster. Int J Adv Manuf Technol(44), 421-427. https://doi.org/10.1007/s00170-008-1840-7

Asp, A., Hentilä, T., & Valkama, M. (2019). Impact of Concrete Moisture on Radio Propagation: Fundamentals and Measurements of Concrete Samples. 16th International Symposium on Wireless Communication Systems (ISWCS). Oulu, Finland: IEEE. https://doi.org/10.1109/ISWCS.2019.8877182

Bezak, E., Takam, R., Yeoh, E., & Marcu, L. G. (2017). The risk of second primary cancers due to peripheral photon and neutron doses received during prostate cancer external beam radiation therapy. Physica Medica, 42, 253-258. https://doi.org/10.1016/j.ejmp.2017.02.018

Birjis, Y., Swaminathan, S., Nazemi, H., Raj, G. C., & Munirathinam, P. (2022). Piezoelectric Micromachined Ultrasonic Transducers (PMUTs): Performance Metrics, Advancements, and Applications. Sensors, 1-29. https://doi.org/10.3390/s22239151

Blanco-Murillo, J., & al, e. (2017). Combined US and UWB-RF imaging of concrete structures for identification and location of embedded materials. Construction and Building Materials, 152, 693-701. https://doi.org/10.1016/j.conbuildmat.2017.07.036

BN., P. (1998). Leaky guided ultrasonic waves in NDT.(PhD Thesis). London: Imperial College of Science, Technology and Medicine.

Building code requirements for structural concrete and commentary. (2008). American Concrete Institute, ACI Committee 318, ACI 318-08.

Cassidy, N. J., Eddies, R., & Dods, S. (2011). Void detection beneath reinforced concrete sections: The practical application of ground-penetrating radar and ultrasonic techniques. Journal of Applied Geophysics, 74, 263-276. https://doi.org/10.1016/j.jappgeo.2011.06.003

Changa, C. Y., Hung, S. S., & Peng, Y. F. (2011). An evaluation of the embedment of a Radio Frequency Integrated Circuit with a temperature detector in building envelopes for energy conservation. In Energy and buildings (pp. 2900-2907). Taiwan: Elsevier. https://doi.org/10.1016/j.enbuild.2011.07.009

Chiba, H., & Miyazaki, Y. (1998). Reflection and Transmission Characteristics of Radio Waves at a Building Site Due to Reinforced Concrete Slabs. Electronics and Communications in Japan, 81(8), 110-120. https://doi.org/10.1002/(SICI)1520-6424(199808)81:8<68::AID-ECJA8>3.0.CO;2-#

Chiba, H., & Miyazaki, Y. (2002). Dependence of Radio Wave Reflection and Transmission Characteristics of Reinforced Concrete Slabs on Frequency and Angle of Incidence. Electronics and Communications in Japan, 85(1), 484-496. https://doi.org/10.1002/ecja.1069

Dalke, R., Holloway, C., McKenna, P., Johansson, M., & Ali, A. (2000). Effects of reinforced concrete structure on RF communication. IEEE Transactions on Electromagnetic Compatibility, 42(4), 486-496. https://doi.org/10.1109/15.902318

Dasa, B. K., & Shyam, A. (2009). Development of compact size penning ion source for compact neutron generator. The Review of scientific instruments, 79, 123305-1-4. https://doi.org/10.1063/1.3054268

Deepa, N., & Sudha, K. (2021). Analysis of single and multiple on-chip antenna for intra-chip wireless communication with four antenna transceiver model. Int. J. Adv. Technol. Eng. Explor, 874. https://doi.org/10.19101/IJATEE.2021.874137

Degertekin, F. L. (2017). Microscale systems based on ultrasonic MEMS - CMOS integration. International Conference on Solid State Sensors and Actuators (Transducers). Kaohsiung, Taiwan. https://doi.org/10.1109/TRANSDUCERS.2017.7994071

Dubinsky, T. J. (2020). Ultrasound Safety: What the Practitioner of Point-of-Care Ultrasound Needs to Know. Journal of Ultrasound in Medicine., 39(10), 1893-1896. https://doi.org/10.1002/jum.15305

Ebensperger, T., Stahlhut, P., Nachtrab, F., & Hankea, S. Z. (2012). Comparison of different sources for laboratory X- ray microscopy. International Workshop on radiation imaging detection. Portugal. https://doi.org/10.1088/1748-0221/7/10/C10008

Eli Leinov, S.Lowe, M. J., & Peter Cawley. (2016). Investigation of guided wave propagation in pipes fully and partially embedded in concrete. Acoustical Society of America, 140, 4528-4539. https://doi.org/10.1121/1.4972118

Ervin, B. L., & Reis, H. (2008). Longitudinal guided waves for monitoring corrosion in reinforced mortar. Measurement Sience and Technology, 19, 1-19. https://doi.org/10.1088/0957-0233/19/5/055702

Esmati, Z., & Moosazadeh, M. (2018). Reflection and transmission of microwaves in reinforced concrete specimens irradiated by modified antipodal Vivaldi antenna. Microw Opt Technol Lett., 60, 2113-2121. https://doi.org/10.1002/mop.31307

Gaul, L., Sprenger, H., Schaal, C., & Bischoff, S. (2012). Structural health monitoring of cylindrical structures using guided ultrasonic waves. Acta Mechanica , 223, pages1669-1680. https://doi.org/10.1007/s00707-012-0634-z

Hirata, A., Funahashi, D., & Kodera, S. (2019). Setting exposure guidelines and product safety standards for radio-frequency exposure at frequencies above 6 GHz: brief review. Annals of Telecommunications, 74, 17-24. https://doi.org/10.1007/s12243-018-0683-y

Hohlig, B., & al, e. (2017). Heat treatment of fresh concrete by radio waves- Avoiding delayed ettringite formation. Construction and Building Materials, 143, 580-588. https://doi.org/10.1016/j.conbuildmat.2017.03.111

Holker, M. (1993). Telecommunications Engineer's Reference Book. Elsevier.

Iftissane, M., Mamouni, A., & Zenkouar, L. (2011). Conception of patch antenna at wide band. International Journal of emerging sciences, 3, 400-417.

Instruments, T. (1998). CC430 combines the ultra-low-pwoer MSP430 Mictocontroller with TI's low power RF technology.

Ishida, H., & Furukawa, H. (2015). Wireless Power Transmission Through Concrete Using Circuits Resonating at Utility Frequency of 60 Hz. IEEE Transactions on Power Electronics, 30(3), 1220-1229. https://doi.org/10.1109/TPEL.2014.2322876

Jiang, S., & Georgakopoulos, S. V. (2011). Optimum Wireless Power Transmission through reinforced Concrete struture. 2011 IEEE International Conference on RFID, 4, 50-56. https://doi.org/10.1109/RFID.2011.5764636

Jiang, X., Lu, Y., Tang, H.-Y., Tsai, J., Ng, E., Daneman, M., . . . Horsley, D. (2017). Monolithic ultrasound fingerprint sensor. Microsyst. . Nanoeng., 3. https://doi.org/10.1038/micronano.2017.59

Kallfass, I., Boes, F., Messinger, T., Antes, J., Inam, A., Lewark, U., . . . Henneberger, R. (2015). 64 Gbit/s transmission over 850 m fixed wireless link at 240 GHz carrier frequency. J. Infrared Millim. Terahertz Waves, 221-233. https://doi.org/10.1007/s10762-014-0140-6

Kessel, R., Hamm, C., & Myers, V. (2017). The safety of diver exposure to ultrasonic imaging sonars. UACE2017- 4th Underwater Acoustics Conference and Exhibition. Greece.

Ko, G.-H., Moon, S.-J., & Kim, S.-H. (2024). Fully Integrated 24-GHz 1TX-2RX Transceiver for Compact FMCW Radar Applications. Sensors, 1-16. https://doi.org/10.3390/s24051460

Lawry, T. J., Wilt, K. R., Ashdown, J. D., Scarton, H. A., & Saulnier, G. J. (2013). A high-performance ultrasonic system for the simultaneous transmission of data and power through solid metal barriers. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 60(1), 194-203. https://doi.org/10.1109/TUFFC.2013.2550

Lee, K. Y., Phua, Y. N., Lim, S. K., You, K. Y., & Cheng, E. M. (2019). Frequency spectrum analysis of lightweight foamed concrete using microwave dielectric measurement technique. Microw Opt Technol Lett., 61, 818-824. https://doi.org/10.1002/mop.31636

Letourneau, A., & al, e. (2017). Development of compact accelerator neutron source. EPJ Web of Conferences. https://doi.org/10.1051/epjconf/201714603018

Li, D., Zhang, S., Yang, W., & Zhang, W. (2014). Corrosion Monitoring and Evaluation of Reinforced Concrete Structures Utilizing the Ultrasonic Guided Wave Technique. International Journal of Distributed Sensor Networks, 1-9. https://doi.org/10.1155/2014/827130

Liu, P. (2014). Wireless Sensor Networks Database: Data Management and Implementation . Sensors & Transducers, 168(4), 173-178.

Liu, W., He, L., Wang, X., Zhou, J., Xu, W., Smagin, N., Xu J. (2019). 3D FEM analysis of high-frequency AlN-based pMUT arrays on cavity SOI. Sensors, 19 (4450). https://doi.org/10.3390/s19204450

Lohne, K. D., Vestrheim, M., & Lunde, P. (27-30 January 2008). Ultrasonic Signal Transmission in Plates- Study of a steel plate immersed in water. 31th Scandinavian Symposium on Physical Acoustics. Geilo, Norway.

Materer, N., Apblett, A., & Ley, T. (2011). Passive Wireless Corrosion Sensors For Transportation Infrastructure. Oklahoma.

MD, B., MJS, L., & P., C. (2003). Ultrasonic guided waves for inspection of grouted tendons and bolts. J Mater Civil Eng, 15(3), 212-218. https://doi.org/10.1061/(ASCE)0899-1561(2003)15:3(212)

Mehta, P. K., & Monteiro, P. J. (2006). Concrete: Microstructure, Properties, and Materials, vol. 3. New York, NY, USA: McGraw-Hill.

Murakami, H., & Fukuda, T. (2024). Development of a High-Sensitivity Millimeter-Wave Radar Imaging System for Non-Destructive Testing. Sensors, 4781. https://doi.org/10.20944/preprints202406.1347.v1

Murata, A., Ikeda, S., & Hayashizaki, N. (2017). Design of an electron-accelerator-driven compact neutron source for non-destructive assay. Nuclear Instruments and Methods in Physics Research B, 406, 260-263. https://doi.org/10.1016/j.nimb.2016.12.024

Mustapha, S., Lu, Y., Li, J., & Ye, L. (2014). Damage detection in rebar-reinforced concrete beams based on time reversal of guided waves. Structural Health Monitoring, 13(4), 347-358. https://doi.org/10.1177/1475921714521268

Naqvi, S., Tahira, S., Warda, B. S., Hasan, R. S., & Kinaan, F. (2019). Awareness of Hazards of X-Ray Imaging and Perception Regarding Necessary Safety Measures to be Taken During X-Ray Imaging Procedures Among Patients in Public Sector Tertiary Hospitals of Karachi, Pakistan. Cureus, 11(5), 1-10. https://doi.org/10.7759/cureus.4756

NASA. (n.d.). Miniaturized High- Speed Modulated X Ray Source (MXS). USA: NASA. Retrieved 10 22, 2020, from https://technology.nasa.gov/patent/GSC-TOPS-51

Nazemi, H., Balasingam, J. A., Swaminathan, S., Ambrose, K., Nathani, M. U., Ahmadi, T., . . . Emadi, A. (2020). Mass Sensors Based on Capacitive and Piezoelectric Micromachined Ultrasonic Transducers-CMUT and PMUT. Sensors, 20, 1-17. https://doi.org/10.3390/s20072010

Neville, A. (1995). Chloride attack of reinforced concrete: an overview. Materials and Structures, 28(2), 63-70. https://doi.org/10.1007/BF02473172

Niederleithinger, E., Wolf, J., Mielentz, F., Wiggenhauser, H., & Pirskawetz, S. (2015). Embedded Ultrasonic Transducers for Active and Passive Concrete Monitoring. Sensors, 15, 9756-9772. https://doi.org/10.3390/s150509756

Nokken, M., & Hooton, R. (2008). Using pore parameters to estimate permeability or conductivity of concrete(Article) . Materials and Structures/Materiaux et Constructions, 41(1), 1-16. https://doi.org/10.1617/s11527-006-9212-y

Noto, K., Koshida, K., Iida, H., & Fukuda, A. (2009). Evaluation of transmission data of diagnostic X Rays through concrete using Monte Carlo simulation. Radiation Protection Dosimetry, 3, 144-152. https://doi.org/10.1093/rpd/ncp037

Ohring, M. (1998). Electronic Devices: How They Operate and Are Fabricated. Elsevier. https://doi.org/10.1016/B978-012524985-0/50003-9

Owen, E. (1997). The origins of 60-Hz as a power frequency. IEEE Industry Applications Magazine, 3(6), 8-14. https://doi.org/10.1109/2943.628099

Park, Z.-T., Choi, Y.-S., Kim, J.-G., & Chung, L. (2005). Development of a galvanic sensor system for detecting the corrosion damage of the steel embedded in concrete structure. Cem. Concr. Res., 35(9), 1814-1819. https://doi.org/10.1016/j.cemconres.2003.11.027

Paudel, B., Li, X. J., & Seet, B.-C. (2024). Sensors, 3220. https://doi.org/10.3390/s24103220

Pereira, E. V., Figueira, R. B., Salta, M. M., & Fonseca, I. T. (2008). Embedded sensors for corrosion monitoring of existing reinforced concrete structures. Mater. Sci. Forum, 587-588. https://doi.org/10.4028/www.scientific.net/MSF.587-588.677

Perveen, K., Bridges, G. E., Bhadra, S., & Thomson, D. J. (2014). Compact passive wireless reinforced concrete corrosion initiation sensor that can be installed in existing steel. 7th European Workshop on Structural Health Monitoring. Nantes, France.

Poole, C., & Darwazeh, I. (2016). Microwave Active Circuit Analysis and Design. Elsevier Ltd. https://doi.org/10.1016/B978-0-12-407823-9.00017-2

Qiu, Y., Gigliotti, J. V., Wallace, M., Griggio, F., Demore, C. E., Cochran, S., & Trolier-McKinstry, S. (2015). Piezoelectric Micromachined Ultrasound Transducer (PMUT) Arrays for Integrated Sensing, Actuation and Imaging. Sensors, 15, 8000-8041. https://doi.org/10.3390/s150408020

R.W.Roussin, Alsmiller, R., & Barish, J. (1972). Calculations of the transport of neutrons and secondary Gamma Rays through concrete for incident neutrons in the energy range 15 to 75MeV. Oak Ridge National Laboratory, Radiation Shielding Information Center, 1-20. https://doi.org/10.2172/4576125

Sammut, S. (2023). Development of a Piezoelectric Micromachined Ultrasonic Transducer Optimised to Operate in the Pore Solution of Reinforced Concrete Structures. Malta: University of Malta. https://doi.org/10.1002/cepa.2175

Sammut, S., Gatt, E., & Borg, R. P. (2017). Chloride ion detection in concrete through Galvanic and Resistivity methods. JJCE Journal Jordan Journal of Civil Engineering, 11(4).

Sammut, S., Gatt, E., & Borg, R. P. (2021). Design of the data transmission component of a micrometre scale chloride ion sensor embedded inside a concrete structure. . Eurostruct. Padova. https://doi.org/10.1007/978-3-030-91877-4_31

Sammut, S., Gatt, E., & Borg, R. P. (2021). Microscale miniaturisation of chloride ion detection sensors for long-term embedding in reinforced concrete structures. Structural Control Health Monitoring. https://doi.org/10.1002/stc.2834

Sammut, S., Gatt, E., & Borg, R. P. (2023). Low frequency Piezoelectric Micromachined Ultrasonic Transducers optimized for concrete structures. Eurostruct. vienna: CE/Papers. https://doi.org/10.1002/cepa.2175

Saniie, J., Wang, B., & Huang, X. (2018). Information Transmission Through Solids Using Ultrasound. 2018 IEEE International Ultrasonics Symposium (IUS). Kobe, Japan. https://doi.org/10.1109/ULTSYM.2018.8579702

Seher, M., Chi-Won, & Kim, I.-Y. (2013). Numerical and Experimental Study of Crack Depth Measurement in Concrete Using Diffuse Ultrasound. Journal of Nondestructive Evaluation, 32(1), 81-92. https://doi.org/10.1007/s10921-012-0161-9

Seki, Y., a, A. T., Hashiguchi, T., Wang, S., Mizuta, M., Wakabayashi, Y., . . . Tanaka, S. (2017). Fast neutron transmission imaging of the interior of large-scale concrete structures using a newly developed pixel-type detector. Nuclear Inst. and Methods in Physics Research, 870, 148-155. https://doi.org/10.1016/j.nima.2017.07.022

Sen, P., & Jornet, J. (2019). Experimental demonstration of ultra-broadband wireless communications at true terahertz frequencies. Experimental demonstration of ultra-broadband wireless communications at true terahertz frequencies (pp. 1-5). cannes: IEEE. https://doi.org/10.1109/SPAWC.2019.8815595

Shin, E., Yeo, H. G., Yeon, A., Jin, C., Park, W., Lee, S.-C., & Choi, H. (2020). Development of a High-Density Piezoelectric Micromachined Ultrasonic Transducer Array Based on Patterned Aluminum Nitride Thin Film. Micromachines, 11(623), 3-10. https://doi.org/10.3390/mi11060623

Siwapornsathain, E., & Lal, A. (2001). Micromachined Ultrasonic Silicon/PZT Transfucer for Underwater Communications. IEEE Ultrasonics Symposium. Wisconsin.

Stankovica, S., Ilic, R., Jankovicb, K., Bojovic, D., & Loncar, B. (2010). Gamma Radiation Absorption Characteristics of Concrete with Components of Different Type Materials. Acta Physica Polonica A, 117, 812-816. https://doi.org/10.12693/APhysPolA.117.812

Svilainis, L., Chaziachmetovas, A., & Dumbrava, V. (2015). Half bridge topology 500 V pulser for ultrasonic transducer excitation. Ultrasonics, 1-16. https://doi.org/10.1016/j.ultras.2015.01.014

Vovchenko, E. D., Isaev, A. A., Kozlovskij, K. I., Shikanov, A. E., & Shkolnikov, E. Y. (2017). An Accelerating Voltage Generator for Compact Pulsed Neutron Sources. Instruments and Experimental Techniques, 60(3), 263-366. https://doi.org/10.1134/S0020441217030150

Wan, X.-M., Wittmann, F. H., Zhao, T.-J., & Fan, H. (2013). Chloride content and pH value in the pore solution of concrete under carbonation. Journal of Zhejiang University, 14(1), 71-78. https://doi.org/10.1631/jzus.A1200187

Wang, M., Zhou, Y., & Randles. (2016). Enhancement of the transmission of piezoelectric micromachined ultrasonic transducer with an isolation trench. J. Microelectromech. syst, 25, 691-700. https://doi.org/10.1109/JMEMS.2016.2577038

Wang, S., Otake, Y., Yamagata, Y., Nagae, T., Fujioka, H., & Hirose, M. (2014). Simulation and design of a simple and easy-to-use small scale neutron source at Kyoto University. Science Direct, 60, 310-319. https://doi.org/10.1016/j.phpro.2014.11.041

Wann, Q., & Wang, C. (2011). A low-voltage low-power CMOS transmitter front-end using current mode approach for 2.4GHz wireless communications. In MicroelectronicsJournal (pp. 766-771). Hunan, China: Elsevier. https://doi.org/10.1016/j.mejo.2011.01.009

Yi, C., Kim, D., Solanki, S., Kwon, J., Kim, M., Jeon, S., . . . Lee, I. (2021). Design and performance analysis of THz wireless communication systems for chip-to-chip and personal area networks applications. J. Sel. Areas Commun., 1785-1796. https://doi.org/10.1109/JSAC.2021.3071849

Zhamova, K. K. (2016). Small-Size X-Ray Sources for Medical Diagnosis. Biomedical Engineering,, 49(6), 354-356. https://doi.org/10.1007/s10527-016-9565-7

Zhang, P., Wittmann, F. H., Zhao, T. j., Lehmann, E. H., & Vontobelc, P. (2011). Neutron Radiography, a Powerful Method to Determine Time-dependent Moisture Distributions in Concrete. Nuclear Engineering and Design, 241, 4758-4766. https://doi.org/10.1016/j.nucengdes.2011.02.031

Zhou, S., Deng, F., Yu, L., Li, B., Wu, X., & Yin, B. (2016). A Novel PassiveWireless Sensor for Concrete Humidity Monitoring. Sensors(16), 1-15. https://doi.org/10.3390/s16091535

Zhou, S., Sheng, W., Deng, F., Wu, X., & Fu, Z. (2017). A Novel PassiveWireless Sensing Method for Concrete Chloride Ion Concentration Monitoring. Switzerland: MDPI. https://doi.org/10.3390/s17122871

Zirbesegger, J., Gebhart, M., Merlin, E., & Leitgeb, E. (2007). Extending the analogue performance of integrated 13.56MHz proximity reader chips. Elektrotechnik & Informationstechnik, 124(11), 369-375. https://doi.org/10.1007/s00502-007-0486-8

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