

HEALTH AND SAFETY ASPECTS OF ELECTRICITY SMART METERS

A STUDY INTO THE POTENTIAL HEALTH EFFECTS OF RADIO FREQUENCY EMISSIONS FROM SMART METERS

Commissioned by Arc Innovations Limited on behalf of New Zealand's energy consumers

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N.B. This is the full study and necessarily involves scientific and engineering terms. A brief summary, with less technical content, is also available.



New Zealand's Centre of Excellence for Power Engineering

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HEALTH AND SAFETY ASPECTS OF ELECTRICITY SMART METERS



Figure 1. A typical Smart Meter and a traditional electromechanical meter

INTRODUCTION TO SMART METERS

“Smart Meter” is a term coined to describe the new electronic electricity meters that are rapidly replacing old electromechanical meters. They are also becoming increasingly referred to as “Advanced Meters”.

These new meters incorporate electronic circuitry that accurately calculates power usage (kW) in order to add up the total energy usage (kWh – the “units” shown on the electricity bill). In addition Smart Meters may be capable of many more functions, such as:

- “Time of use metering” – recording when, as well as how much, energy has been used
- Measuring voltage amplitude and quality – recording fluctuations and distortion of the nominal 230V, 50Hz waveform
- Switching of large loads (e.g. hot water heater) in response to system signals (function already carried out on older installations using separate ripple control relay)
- Networking with “Smart” appliances inside the house – e.g. potential to turn on tumble dryer when electricity demand/price is lowest

In order to make best use of these capabilities, the Smart Meters need to be able to communicate some or all of their measurements to the electricity companies for billing and other purposes, and also to receive commands from the electricity company for set-up and load control purposes.

Hence at least one communication channel is necessary between the meter and some remote collection/control point. There are a number of possibilities for such channels, including:

- Power Line Carrier (PLC) – data signals are superimposed on the power line itself
- Wireless Radio Frequency (RF) – data signals are transmitted and received by radio
- Ethernet/Broadband – data signals are sent over the broadband data/telephone network (usually copper or optic fibre)

Why the industry wants Smart Meters

As discussed above, some meters are smarter than others, depending what capabilities they have, or can be upgraded to incorporate. In the simplest case they replace the meter reader by sending the monthly reading electronically. This is known as Automatic Meter Reading (AMR). This has the obvious benefits of saving staff and transport costs, eliminating reading errors and the need to estimate bills when the meter cannot be reached.

Advanced Metering Infrastructure (AMI) is a much more significant concept, requiring the smarter Smart Meters with the extra functionality. With this infrastructure in place the electricity companies have the potential to match demand and available supply, for instance by:

- disconnecting non-essential devices when demand is exceeding supply
- bringing Distributed Generation (DG) sources (such as small wind farms and solar generators) online when demand is exceeding supply
- sending real-time pricing signals to encourage/enable customers to run the tumble dryer or recharge the Electric Vehicle (EV) when there is excess supply available

The above concepts are often known as Demand Management (DM), or Demand-side Management (DSM).

Why Smart Meters are good for the customer and NZ Inc

At present load demand is very 'peaky'. That is, the peak electricity usage is very much higher than the average. This requires having the capacity in generators, transmission lines and distribution equipment to meet the peak. As the peak increases, so does the need for new generation, transmission lines and distribution systems.

With much more detailed information available regarding the time when individual households, and potentially even when individual appliances, are using power, users have the opportunity to be much more circumspect about their consumption of electricity. It is already possible for many customers with Smart Meters to keep continuous tabs on their electricity usage via the internet. With pricing based on available supply versus demand, there are opportunities for saving money when using large amounts of energy (tumble drying, EV charging, water heating). With controllable loads also connected (very likely in the case of EV charging), demand can be shaped to avoid building new infrastructure, thus keeping costs and environmental concerns under control.

This is a real chance for the industry and customers alike to change the pattern of consumption to maximize use of renewable energy (e.g. solar, wind and hydro), whilst minimizing use of fossil fuels and overall energy, and reducing the need for extremely expensive and unpopular grid upgrades, such as new transmission lines.

POTENTIAL HEALTH CONCERNS OVER SMART METERS

As with any new technology there are always potential concerns as to whether there are any health downsides that may have been overlooked. In the case of Smart Meters there is valid concern for a close look when the communications medium is radio. This is because Radio Frequency (RF) waves cause heating of any body that absorbs power from them, depending on their frequency and intensity. (This heating effect is used deliberately in Microwave ovens).

POTENTIAL HEALTH EFFECTS OF WIRELESS RF TRANSMISSION

Basics of the electromagnetic spectrum

Radio transmissions use a part of the electromagnetic (EM) spectrum, which ranges from a steady state (like the earth's magnetic field – zero frequency), through radio frequencies, microwaves, infra-red, visible light, ultra-violet, X-rays, Gamma rays and theoretically up to an infinite frequency. In the early part of the 20th century work by Max Planck, Albert Einstein and Louis-Victor de Broglie showed electromagnetic energy to have both wave-like and particle-like properties. From the wave perspective, there is a direct relationship between wavelength, λ , and frequency, f , described by the following well-known equation:

$$v = f\lambda$$

where v is the velocity (or speed) of propagation of the waves through the transmission medium. v is the speed of light (as light is part of the EM spectrum). In free space this speed is about 300 million metres per second. Frequency is measured in cycles (or waves) per second, which have the scientific unit of hertz (Hz), named after the German physicist Heinrich Hertz. Hence a radio transmission with a wave frequency of 1 billion Hz (which means 1 billion waves pass a given point per second) has a wavelength of about 0.3m (30cm). For the sake of brevity scientific notation will be used from now on, instead of million, billion and so on.¹

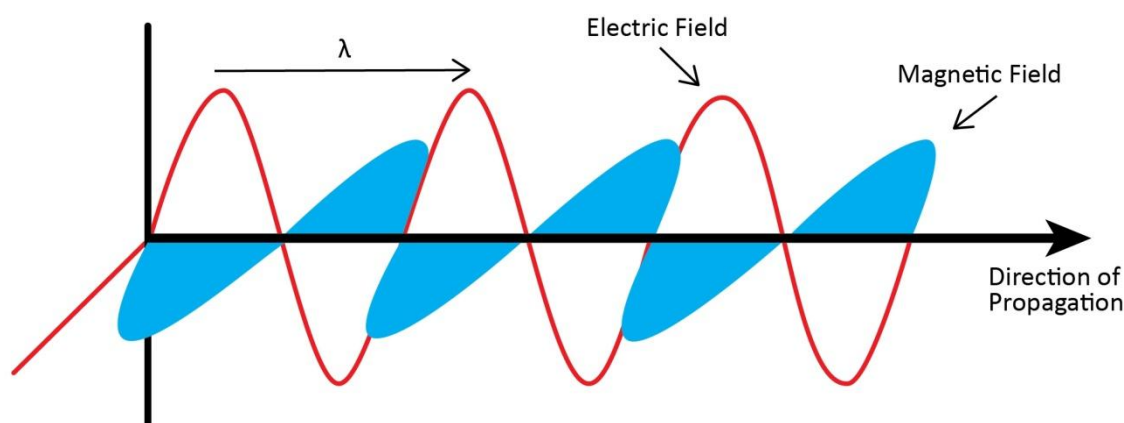


Figure 2. Visualization of an electromagnetic wave

From the particle perspective, there is a direct relationship between the frequency of the wave, f , and the energy of the equivalent particles (known as photons), E , described by the following equation:

$$hf = E$$

where h is Planck's constant, approximately 6.63×10^{-34} Js (joule-seconds) or 4.14×10^{-15} eVs (electron-volt-seconds). Hence a radio transmission with a wave frequency of 1 GHz (10^9 Hz) can be shown to equate to a stream of photons each with an energy of about 660×10^{-27} J (joules, SI² unit of energy) or 4.14×10^{-6} eV (electron-volt, physical unit of energy). Each photon has the smallest possible amount of energy related to this frequency of EM radiation, also known as a quantum.

¹Scientific notation: for example: 2,400,000,000Hz = 2.4×10^9 Hz = 2.4 billion Hz = 2.4GHz

Scientific	10^{-12}	10^{-9}	10^{-6}	10^{-3}	10^0	10^3	10^6	10^9	10^{12}
Common	trillionth	billionth	millionth	thousandth	one	thousand	million	billion	trillion
Engineering	pico, p	nano, n	micro, μ	milli, m		kilo, k	Mega, M	Giga, G	Tera, T

² SI stands for "Système International d'unités" or International System of units, used for scientific purposes

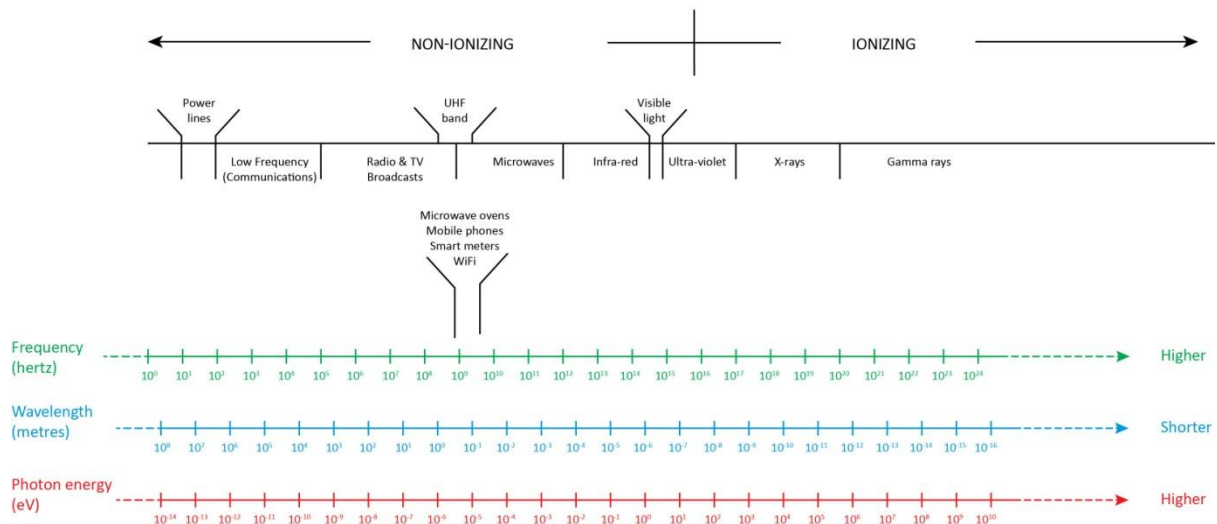


Figure 3. The electromagnetic spectrum

Ionizing versus non-ionizing radiation

Before getting worried by the term “radiation” it is worth remembering that all life on earth depends entirely upon the presence of radiation, in the form of infra-red, visible and ultra-violet (UV) light. Without radiation the planet would rapidly cool and all life would become extinct. “Radiation” has unfortunately got its bad name from the so-called “nuclear radiation” (alpha particles, beta particles and gamma radiation) associated with nuclear power and atomic weapons.

When the quantum energy becomes sufficient to liberate an electron from an atom, creating a positive ion, the radiation can be described as “ionizing”. It can be shown that this does not occur until the energy per quantum reaches over 10eV [1], corresponding to a frequency of about 2.42×10^{15} Hz and a wavelength of 1.24×10^{-7} m (124 nanometres, nm), which is in the UV part of the spectrum. Ionization creates free radicals which can damage DNA. Slightly lower energy photons (above about 3eV, corresponding to 400nm, the transition between visible light and UV – soft UV) have also been shown to cause molecular damage by non-ionizing means (such as sunburn) [2]. This is why it is crucial to cover up from the sun.

However, the part of the EM spectrum used for radio frequency (RF) communication by Smart Meters is properly defined by the International Telecommunications Union (ITU) as the Ultra High Frequency (UHF) region, which ranges from 300MHz to 3GHz. (The word “microwave” is often applied to RF above 1GHz (such as “microwave” ovens, which typically operate at 2.4GHz). Even at 3GHz, the quantum energy (12.4ueV) is 240,000 times lower than the softest UV¹. Clearly this radiation is “non-ionizing” and there is absolutely nobody who disputes this.

Standards for safe exposure to non-ionizing radiation

Exposure to high levels of RF radiation is known to cause health issues in humans, due to the heating effects of the radiation [1].

It has been pointed out in the literature [3] that, before the advent of UHF and microwave radio communications, the background levels of radiation in the corresponding portion of the EM

¹Radio transmitters also radiate small amounts of energy at integer multiples (known as harmonics) of their frequency. At 3GHz the softest UV would equate to the 800,000th harmonic - anything above the 3rd harmonic is generally undetectable.

spectrum on earth can be estimated to be below 10^{-14}W/m^2 (watts per square metre), whereas they are now around 10^{-3}W/m^2 and increasing, as communications technologies proliferate. Many researchers are quite correctly continually questioning whether there are any detrimental effects being caused by this. At the same time it is perhaps worth remembering that the average intensity of solar radiation reaching the earth's surface is about 200W/m^2 and that average life expectancy in "developed, low mortality" nations [4] was around 80 years in 2000, as opposed to about 50 years in 1900.

Because of this concern, many national and international bodies study the scientific literature and produce standards and recommendations for safe levels of exposure to RF fields. Among these are the World Health Organization (WHO), which maintains a database on all relevant research, the International Commission on Non-Ionizing Radiation Protection (ICNIRP), Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), National Council on Radiation Protection and Measurements (NCRP), Federal Communications Commission (FCC), Institute of Electrical and Electronic Engineers (IEEE), the latter three being USA-based organizations.

The main publications on which national and international standards are based are shown in Table 1.

Organization	Title	Date	Publication Details
ICNIRP	Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300GHz)	April 1998	Health Physics, April 1998, Volume 74, Number4:494-522
ARPANSA	Maximum Exposure Levels to Radiofrequency Fields — 3 kHz to 300 GHz	March 2002	ARPANSA Radiation Protection Series Number 3
NCRP	Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields	1986	NCRP Report No. 86 (1986)
FCC	Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields	August 1997	FCC Office of Engineering & Technology (OET) Bulletin 65
IEEE	IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz	April 2006	IEEE Std C95.1™-2005

Table 1. Publications on which national and international standards are based

In the USA, FCC OET Bulletin 65 [8], based on NCRP report 86 [7], is used as the standard requirement for RF exposure, despite the existence of American National Standards Institute (ANSI) ANSI/IEEE Std C95.1™-2005 [9]. Most other national standards, including ANSI/IEEE Std C95.1™-2005, are based tightly on the ICNIRP guidelines. This includes NZS2772:Part 1: 1999, Radiofrequency Fields, Part 1 – Maximum Exposure Levels – 3kHz to 300GHz [10], which is the applicable standard in NZ. NZS2772:Part 1: 1999 is generally slightly more restrictive than FCC OET Bulletin 65 and aligns exactly with ANSI/IEEE Std C95.1™-2005.

For this reason we will concentrate on NZS2772:Part 1: 1999, as it is the applicable NZ standard and ANSI/IEEE Std C95.1™-2005, as it is the most recent and informative of the above documents.

To make sense of the standards it is necessary to understand the rationale behind them. The standards define a "basic restriction" in terms of the maximum amount of RF power that can be absorbed per kg by a person (watts per kilogram), averaged throughout their whole body mass. They then go on to define a maximum localized amount of RF power that can be absorbed in any 10g of tissue within different parts of the body.

These power levels are based primarily on the temperature rise caused by absorbing this amount of RF power (just as sunlight falling on us raises our temperature).

Because it is very difficult to measure how much RF power is absorbed from a given product, the standards specify the calculated “power flux density” in W/m^2 which would cause that much RF power absorption. (This is dependent on frequency, because some frequencies are more readily absorbed by body tissue than others.) To do this, standard models of the human body are employed. It is hence necessary for a company to prove that the “power flux density” of any product it supplies complies with the relevant standard.

Quoting from page 4 of NZS2772:Part 1: 1999:

“In setting limits, ICNIRP identified RF field values above which adverse biological effects could be confirmed by independent laboratory studies. These values were used as benchmarks. For example, for exposures in the frequency range above about 10MHz, the benchmark was an absorption of RF power equivalent to a whole body average Specific energy Absorption Rate (SAR) of 4W/kg (watts per kilogram). The biological effect detected at this level is the reduced endurance to perform tasks in experimental animals, when their temperature was raised about 1°C as a result of the RF field exposure.

To derive exposure limits from this SAR benchmark, a safety factor of 10 was incorporated so that workers would not be exposed to more than 1/10th of this level (i.e. 0.4W/kg). For the general public, an additional safety factor of 5 was incorporated into the exposure limits. Thus the exposure limits for the general public are set at 1/50th of the benchmark level (i.e. 0.08W/kg). These levels provide basic restrictions for frequencies at which the SARs are limiting values.”

Further, pages 4 and 5 of NZS2772:Part 1: 1999 state:

“There is currently a level of concern about RF exposure, which is not fully alleviated by existing scientific data. It is acknowledged that data regarding biological effects, at levels below those determined in this Standard, are incomplete. However, as these data are neither clear nor consistent, these have not been used in setting the levels for basic restrictions in the ICNIRP Guidelines or this Standard. It should be further noted that it is not possible to logically prove with certainty that any environmental agent will not cause an adverse health effect. This is an inherent limitation of any process, including the scientific method, that relies on inductive reasoning.

Research is continuing in many countries into possible effects on health arising from RF exposure. In recognition of this, the Committee will continue to monitor the results of this research and, where necessary, issue amendments to this document. Generally, it is therefore sensible in achieving service or process requirements to minimize unnecessary or incidental RF exposure.”

Quoting from annex B.3, page 39 of ANSI/IEEE Std C95.1™-2005:

“A number of speculative and established mechanisms of RF interactions with biological systems have been proposed and representative samples are listed below. Most of these are speculative and have no support from a review of the biological literature, i.e., no consistent low level effect. The last three categories (thermal, strong field effects, and electrostimulation) are established effects that are used as the basis of this standard.”

This document, which runs to 250 pages and references 1143 papers and 144 books, concludes that the ICNIRP guideline for a whole body average SAR of 4W/kg is still defensible in the light of research published up to and including 2005.

Nevertheless, research papers continue to be published concerning non-thermal, biological effects of SARs much lower than those specified in the standards, including by well respected teams and individuals [Salford et al]. Many more such papers are listed in the WHO EMF project database. In addition to this, a phenomenon known as electromagnetic hypersensitivity (EHS) has been reported [Havas et al], in which individuals claim to be sensitive to very small RF power flux densities, well below those necessary to meet the SAR limits. However there are also review papers from reputable sources highlighting a lack of consistency in such published findings [Rubin].

Without turning back the clock to the days before Hertz and Marconi, radio, TV, CB, walky-talkies, microwave ovens, cordless/mobile phones and WiFi, following the standards based on the established and recognized phenomena, tempered by the advice in NZS2772 to “minimize unnecessary or incidental RF exposure”, seems to provide the best direction.

Standard	Basis	SAR – WBA	SAR – H & T	SAR - Limbs	S_{eq} (W/m ²) UHF	S_{eq} (W/m ²) Microwave
NZS2772:Part 1: 1999 New Zealand	ICNIRP	0.08W/kg (6 min average)	2 W/kg (6 min average over 10g)	4 W/kg (6 min average over 10g)	$f_M/200$ (6 min average) $5f_M$ (max rms) 400MHz – 2GHz	10 (6 min average) 10,000 (max rms) 2GHz – 10GHz
ARPANSA RP3 Australia	ICNIRP	0.08W/kg (6 min average)	2 W/kg (6 min average over 10g)	4 W/kg (6 min average over 10g)	$f_M/200$ (6 min average) $5f_M$ (max rms) 400MHz – 2GHz	10 (6 min average) 10,000 (max rms) 2GHz – 10GHz
ANSI/IEEE Std C95.1™-2005 USA	ICNIRP	0.08W/kg	2 W/kg (average over 10g)	4 W/kg (average over 10g)	$f_M/200$ (30 min average) 400MHz – 2GHz	10 (30 min average) 2GHz – 5GHz
FCC OET Bulletin 65 USA	NCRP	0.08W/kg	1.6 W/kg (average over 1g)	4 W/kg (average over 10g)	$f_M/150$ (30 min average) 300MHz – 1.5GHz	10 (30 min average) 1.5GHz – 100GHz

Table 2. Summary of Maximum Personal Exposure (MPE) limits for the general public in various standards, at frequencies used by Smart Meters

Table 2 summarizes those parts of the United States, Australia and New Zealand standards that are relevant to the frequencies used by Smart Meters. (There is a great deal of further information in each standard that is not directly relevant.) In explanation of the table:

- SAR – WBA: Whole Body Average Specific Absorption Rate – i.e. a 50kg person can safely absorb up to 4W of RF power, if it is spread uniformly throughout the body. All standards agree on this figure; NZS2772 and RP3 specifically refer to temporal averaging over a 6 minute period¹, whereas a 30 minute averaging time is implied by the others. Because power is unlikely to be spread uniformly it is necessary to also specify maximum SAR for specific parts of the body:
- SAR – H & T: Specific Absorption Rate for Head and Trunk – FCC restriction is tightest, allowing a maximum of 1.6W/kg in any 1g of contiguous tissue in the shape of a cube. All the others allow a maximum of 2W/kg in any 10g of contiguous tissue in the shape of a cube. Again the temporal averaging period is either explicit or implied as per above.

¹This means that the average power in any given 6 minutes must not exceed 4W. e.g. 8W continuous for 3 minutes, followed by 0W for 3 minutes is acceptable; 8W continuous for 4 minutes is not.

- SAR – Limbs: Specific Absorption Rate for Limbs (including hands, feet, fingers & toes) – All the standards allow a maximum of 4W/kg in any 10g of contiguous tissue in the shape of a cube. Again the averaging period is either explicit or implied as per above. The lower value for head and trunk is designed to take into account such factors as the poorer cooling of the eyeballs and testes.
- S_{eq} (W/m²) UHF and Microwave: These columns give the equivalent power flux densities to result in SAR within the above limits. NZS2772 and RP3 give both a 6 minute time average and a maximum rms¹ instantaneous limit. The others give only a 30 minute average limit. The interpretation of these two columns is:
- In the lower part of the frequency band, 400MHz – 2GHz (300MHz – 1.5GHz for FCC), S_{eq} is limited to [frequency in MHz (f_M) divided by 200] W/m² (or divided by 150 for FCC). In the higher part of the frequency band, above 2GHz, S_{eq} is limited to 10W/m². These are average levels over a 6 minute period (NZS2772 and RP3) or a 30 minute period (IEEE and FCC). NZS2772 and RP3 also define a maximum instantaneous S_{eq} limit exactly 1,000 times higher than the average, allowing for short pulses of RF power.

Studying the standards it becomes clear that taking the limits specified by NZS and RP3, in conjunction with SAR - H & T from FCC, gives the most stringent set of requirements. We shall hence investigate radiation from Smart Meters with respect to these limits. Note that the standards have some specific additional provisions for mobile and portable devices. They are not appropriate to this paper and are not considered.

RF EMISSIONS OF SMART METERS

As far as RF emissions are concerned, Smart Meters fall broadly into 3 categories:

1) Meters using cellular data modems at 900MHz, 1.8GHz or 2.1GHz. In NZ these meters are all believed to be currently on the Vodafone 900MHz/1.8GHz GPRS network. The data modems have a maximum nominal RF output power of 2W, although much lower power is used when in a good coverage area. This is the same power level as using a regular cellular mobile phone to make a voice call or send an SMS text. Very little data is transferred by these meters, so the duty cycle and hence average power output are very much less than 2W. The data that is transferred travels between the meter and the nearest cell tower, exactly as for a mobile call or SMS text.

2) Meters using a mesh network in the 900MHz Industrial, Scientific & Medical (ISM) band. In NZ this band is from 921-928MHz, where the Ministry of Economic Development (MED) General User Radio Licence (GURL) for Short Range Devices (SRDs) applies [11]. The GURL limits the peak power that can be transmitted by any device to a maximum of 4W (EIRP - in practice it will be less than this as discussed later. Note that GURL limits are in place to reduce interference between different users of the band, not to comply with NZS2772 requirements). The mesh network topology relies on nearby meters communicating with at least one, and potentially up to about 30, of their near neighbours, as shown in Figure 4. This has the operational advantage of allowing data to be routed along a choice of paths, providing resilience if one path becomes unavailable. The mesh topology also employs “forwarding routers” which are typically mounted on power poles, to connect sub-meshes together, “Wide Area Network (WAN) gates” and “Take-out points” to connect the mesh back to the electricity company’s data centre. These parts of the system may use the 900MHz ISM band, the 5.8GHz ISM band, the cellular network or a wired solution, such as ADSL (as used for home broadband over telephone lines).

¹rms stands for “root mean square” and is used to define the effective heating value of alternating waveforms.

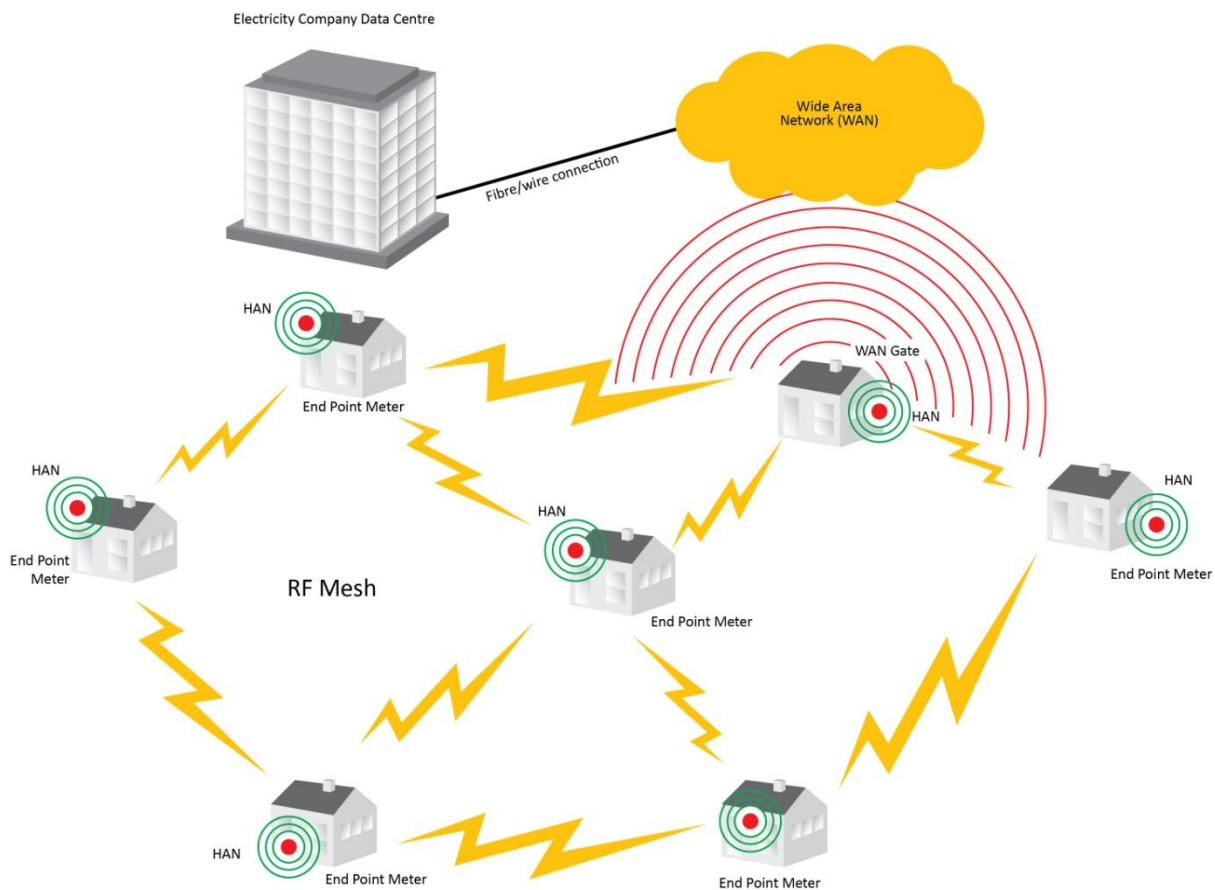


Figure 4. RF Mesh network of Smart Meters also equipped with RF HAN

3) Meters using one or other of the above, in conjunction with a local Home Area Network (HAN) in the 2.4GHz ISM band. In NZ this band is from 2.400-2.483GHz, where the Ministry of Economic Development (MED) General User Radio Licence (GURL) again applies [11]. The GURL limits the peak power that can be transmitted by any device to a maximum of 4W (EIRP - in practice it will be less than this as discussed later).

There are also a few Smart Meters using satellite communications in rural areas, but they are not covered in this paper.

Clearly the absolute worst-case SAR values would occur if transmission was continuous and all the transmitted power was absorbed by a body. For the cellular data modem case this is 2W, so if the power was totally absorbed by a body of at least 25kg and no more than 1.6W if it was absorbed uniformly in any 1kg cube of the head or trunk, all standards would be satisfied. In practice only a small fraction of the power will be absorbed (even if the body completely envelopes the antenna), but the power distribution is non-uniform close to the antenna, so further investigation is necessary.

Propagation of RF fields

As discussed earlier, RF radiation consists of waves of electric and magnetic fields (see Figure 2). (The particle model is more appropriate to much higher frequency parts of the EM spectrum). The properties of the fields change with distance from the transmitting antenna, measured in multiples of the wavelength, λ , as described in Table 3.

Distance ¹	Field type	900MHz	1.8GHz	2.4GHz
0 to $\lambda/2\pi$	Reactive near	0 to 5cm	0 to 2.5cm	0 to 2cm
$\lambda/2\pi$ to $\lambda/2$	Boundary near	5cm to 17cm	2.5cm to 8cm	2cm to 6cm
$\lambda/2$ to $\sim 3\lambda$	Radiating near	17cm to 100cm	8cm to 50cm	6cm to 37cm
$> \sim 3\lambda$	Far	$> 100\text{cm}$	$> 50\text{cm}$	$> 37\text{cm}$

Table 3. Electromagnetic field properties versus distance from radiating element

At a distance of more than a few wavelengths from the transmitting antenna, known as the “far field”, the relationship between the two fields is fixed and the radiation can be described as “plane wave”. The relationship is known as the “characteristic impedance of free space”, such that:

$$S = E.H = H^2.Z_0 = \frac{E^2}{Z_0}$$

where Z_0 is the characteristic impedance (approximately 377 ohms), E is the electric field strength (in volts per metre), H is the magnetic field strength (in ampères, or amps, per metre) and S is the electromagnetic power flux density (in watts per square metre). To prove that Smart Meters are compliant with the safety standards described previously, the values of S experienced by a person must be lower than the values of S_{eq} from Table 2.

At distances closer to the transmitting antenna, known as the “near field”, the actual field impedance Z is not necessarily equal to Z_0 and hence both E and H must be measured to obtain accurate results. However, it can be shown that Z is within 10% of Z_0 for distances greater than about half a wavelength (radiating near field) from the antenna, so that E, H or S can be measured for compliance to the standards at distances greater than 17cm for 900MHz, 8cm for 1.8GHz and 6cm for 2.4GHz.

Antennas and gain

There is no such thing as a perfect antenna. However it is convenient to think of a hypothetical antenna, known as an “isotropic radiator”. An isotropic radiator, like a perfectly round light bulb, would radiate all the power delivered by the transmitter, spreading it evenly in all directions. Thus the field would spread out in a perfect sphere, carrying on for ever to the limits of the universe. However, nothing is perfect, and in practice some of the power is wasted in mismatching between the transmitter and the antenna and the field pattern of the power that is radiated is influenced by the shape of the antenna and surrounding objects. The antenna is often deliberately designed to focus the radiation in a particular pattern, like a spotlight. In this case it is said to have “gain”, which is normally measured in dBi², decibels relative to isotropic. Because the focussed beam can have many shapes and some radiation still goes in unwanted directions, antennas are usually characterized by beam patterns (known as polar plots) for both horizontal and vertical axes (see Figure 5). The greatest power flux density (S) is generally in the centre of the beam and is hence the most likely to infringe the safety standards. For the antenna of Figure 5, the gain is 11dBi (0.1W transmitter power results in about 1.25W EIRP). The “half-power beam-width” in the vertical plane (red trace) is about 30° (the red trace cuts the blue -3dB circle at 75° and 105° from vertical).

¹ π is the ratio of the circumference to diameter of a circle, and equals approximately 3.14. Hence $\lambda/2\pi$ is roughly one sixth of a wavelength. The symbol, \sim , is used to indicate “approximately”. The symbol, $>$, means “greater than”.

² dB (decibel): The dB is used as a relative logarithmic (log) measure, such that a power of x times is equal to $10\log_{10}x$ dB. Relative power of 1 equals 0dB; of 2 = 3dB; of 4 = 6dB; of 8 = 9dB; of 10 = 10dB; of 100 = 20dB; of $\frac{1}{2}$ = -3dB; of $\frac{1}{10}$ = -10dB

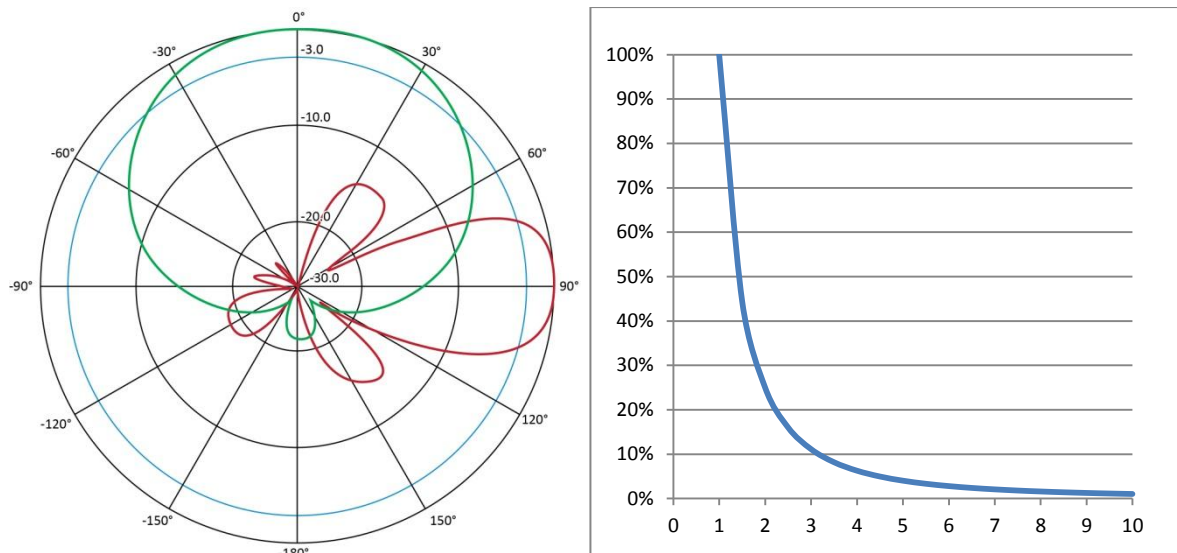


Figure 5. Polar plot for example antenna and S, as a percentage, versus relative far-field distance from antenna (inverse square law)

The “half-power beam-width” in the horizontal plane (green trace) is about 80° (the green trace cuts the blue -3dB circle at -40° and $+40^\circ$). The red trace also shows that at an angle of 25° above or below the centre of the beam, the power flux density (S) is -10dB down – i.e. reduced to $1/10^{\text{th}}$ – and at 30° it is -20dB down – i.e. reduced to $1/100^{\text{th}}$. There are noticeable “side-lobes” about 50° either side of the main beam, where the power flux density (S) is at least -13dB down – i.e. reduced to $1/20^{\text{th}}$.

Regardless of type and gain of antenna, in the far field both the electric (E) and magnetic (H) field strengths fall off linearly with distance from the antenna, causing the power flux density (S) to fall off with the square of the distance. Hence S has an “inverse square law” relationship with distance. E.g. as the distance from the antenna doubles, S becomes $\frac{1}{4}$ or 25%; at 10 times the distance, S is reduced to 1%. An antenna with a gain of 10dBi will produce a maximum S, at any distance, of 10 times that from an isotropic radiator.

Reflections

Surrounding objects, such as walls and the ground, also influence the field pattern and can cause S at any point to be either reduced or increased. This is because the objects can reflect part of the field in such a way that the direct and reflected signals add or cancel. Hence the actual physical environment the antenna is mounted in is important. FCC OET65 states the worst-case as producing a four-fold (6dB) increase in S and recent experimental work into measuring real-world SARs in highly reflective environments [12] agree with this (5.5dB @ 900MHz). Another paper [13] shows that such S “hot-spots” can be even more significant than this, in extremely reflective environments, such as inside a steel shipping container or a lift/elevator, where there are multiple reflections. However, in these environments, RF communications would in any case be of little use.

When relatively close to a radiating source (such as a WiFi router, cordless phone base unit or microwave oven), the field across an object, such as a human body, will not be uniform, because different parts of the body will be significantly closer to the source and reflections than others. This is most true when extremely close, as with a mobile or cordless phone. When relatively far from the source (such as a TV or radio broadcast antenna), the field will be relatively uniform.

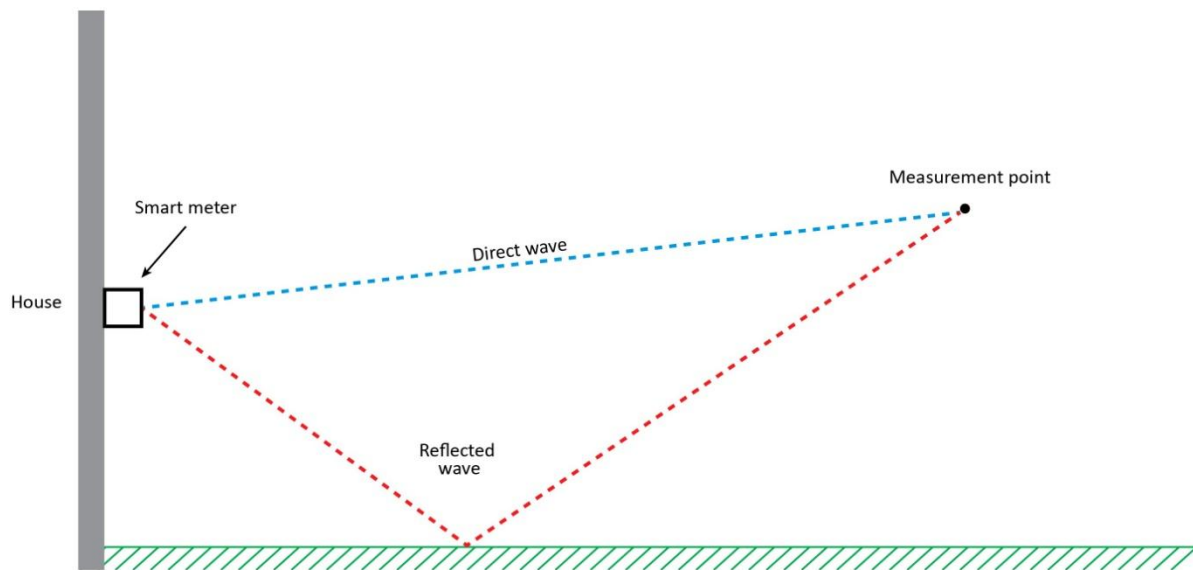


Figure 6. Direct wave and reflected wave combining at measurement point

Obtaining figures for S from Smart Meter transmitters

There are three ways to obtain figures for S:

- Mathematical modelling
- Computational modelling
- Field Measurements

Maximum far field values for S, assuming no reflections, can be mathematically calculated from:

$$S_{ff} = \frac{P \cdot G}{4\pi R^2}$$

where P is the transmitter power, G is the antenna gain and R is the distance from the antenna. Multiply this by 4 to give the worst-case reflection situation. Expressions also exist for surface, near field and transition regions [8], but they rely heavily on the physical attributes of the antenna, so would have to be calculated for every antenna type used. The product P.G is also known as the Effective Isotropic Radiated Power (EIRP) and it is actually this that is limited to 4W in the 900MHz and 2.4GHz bands by the NZ GURL. (Since any practical radiating antenna will have directional gain greater than 1, the total power radiated **must** be less than 4W).

Mathematical modelling using 3D electromagnetic (EM) finite-difference time-domain (FDTD) solver software has been reported in [12] and other publications.

Extensive independent field measurements on a number of manufacturer's Smart Meters in many different configurations have been carried out by the Electric Power Research Institute (EPRI) [14, 15, 16].

Table 4 presents calculated results for S_{ff} versus distance for the frequencies of interest, assuming the NZ GURL maximum limits are used and either 50% or 100% duty cycle is used for 900MHz Mesh and 2.4GHz HAN. Duty cycle is the percentage of time that RF is being transmitted. For Smart Meters, at each of these frequencies, the same antenna is used to transmit and receive data (known as half-duplex operation) and the duty cycle will actually always be less than 50% in normal

operation (generally in the range of 1% to 5% [15]); in the case of a fault, a 100% duty cycle might be possible for a short time (measured in seconds, rather than minutes) before an automatic reset occurs. Typically the switch between transmit and receive would happen many times per minute, so the 6 minute averaging period of the more stringent standards is clearly satisfied. Because the GURL limits EIRP, the gain of the antenna is irrelevant.

Distance	900MHz Mesh 2.4GHz HAN 50%	900MHz Mesh 2.4GHz HAN 100%	Combined 50%	Combined 100%	900MHz average limit	2.4GHz average limit	Combined average limit
0.5m	0.64	1.27	1.27	2.54	4.5	10	7.25
1m	0.16	0.32	0.32	0.64	4.5	10	7.25
2m	0.04	0.08	0.08	0.16	4.5	10	7.25
5m	0.006	0.013	0.013	0.026	4.5	10	7.25
10m	0.002	0.003	0.003	0.006	4.5	10	7.25

Table 4. S_{ff} in W/m^2 versus distance for 900MHz Mesh and 2.4GHz HAN at maximum EIRP allowed by NZ GURL

Note: Blue figures indicate that 0.5m is not properly in the far field for 900MHz antenna

In the case of cellular modems at 900MHz or 1.8GHz the GURL does not apply and, with the 2W maximum power, the EIRP does depend on antenna gain. Of course the cellular modem does not spend all the time transmitting (mobile network charges alone would prohibit this). Duty cycles of less than 1% would be expected, with an extreme case of 10% (30s of transmission over a 300s, 6 minute averaging period). Nonetheless Table 5 also considers the 50% duty cycle case.

Distance	900MHz/1.8GHz 3dBi 10%	900MHz/1.8GHz 6dBi 10%	900MHz/1.8GHz 3dBi 50%	900MHz/1.8GHz 6dBi 50%	900MHz average limit	1.8GHz average limit
0.5m	0.127	0.255	0.64	1.27	4.5	9
1m	0.032	0.064	0.16	0.32	4.5	9
2m	0.008	0.016	0.04	0.08	4.5	9
5m	0.0013	0.0025	0.006	0.013	4.5	9
10m	0.0003	0.0006	0.002	0.003	4.5	9

Table 5. S_{ff} in Wm^{-2} versus distance for 900MHz and 1.8GHz GPRS modem at maximum power of 2W for various antenna gains and transmit duty cycles

Note: Blue figures indicate that 0.5m is not properly in the far field for 900MHz antenna

Worst-case calculations

Using the mathematically derived results in Tables 4 and 5 and multiplying them by 4, for the additive reflection case, it can be seen that, at a distance of 1m from the antenna/s, the highest case is for simultaneous 100% 900MHz and 2.4GHz transmission from adjacent antennas, yielding 35% of the allowable MPE $\{(4 \times 0.64)/7.25\}$. Therefore, at a distance of 1m or more from any or all of the antennas, one can stand there for ever, whatever the duty cycle, without exceeding the MPE limits.

At a distance of 0.5m, with 100% duty cycle of the 2.4GHz HAN, 51% of the MPE could be reached. At a distance of 0.5m, with 50% duty cycle of the 1.8GHz GPRS, with 6dBi antenna, 56% of the MPE could be reached.

At a distance of 0.5m, with 100% duty cycle of the 900MHz Mesh, or 50% duty cycle of GPRS with 6dBi antenna, the MPE could be exceeded if one stayed there for more than 5 minutes (using the 6 minute average) or 26 minutes (using the 30 minute average).

It should be noted that the above takes into account the additive heating nature of RF fields of different frequencies from the same Smart Meter, but does not consider existing RF sources already present, such as microwave ovens. The duty cycles used are worst case, the EIRPs are the maximum allowable under NZ licence regulations and both are **extremely** unlikely to be approached in practice. For instance, one type of Smart meter using 900MHz RF Mesh currently being deployed in NZ generally has a nominal EIRP of 0.1W {25mW radio, 6dBi antenna} – i.e. only 2.5% of the 4W assumed in Table 4. Unless in a fringe coverage area, GPRS modem output is more likely to be 0.1W than the 2W assumed – i.e. only 5% of the 4W assumed in Table 4. Furthermore, the figures for S in Tables 4 and 5 assume one is standing right in the centre of the antenna beam, which is also unlikely.

Highly detailed field studies and measurements on different Smart Meters have been carried out by EPRI [14, 15, 16]. In [15], based on a real Smart Meter using 900MHz RF Mesh technology they concluded:

“For the type of smart meter and relatively small sample of meters characterized, the results indicate that in front of the meters, even with 10 meters nominally rated at ¼ watt operating continuously (100% duty cycle) on the same rack, the exposure level a foot (~30cm) from the center of the rack was a small fraction of the FCC exposure limit for the general public and, as expected, diminished with increasing distance from the rack. The power density levels were comparably lower behind the meters. An extensive analysis of smart meter transmissions for almost 47,000 meters in southern California was included in the EPRI study. The report estimated that 99.5% of the sample was operating at a duty cycle of about 0.22% or less, a value that translates to 3 minutes and 10 seconds of transmitting over a day; the maximum duty cycle associated with any meter did not exceed 5%. The duty cycle for cell relays within the same sample did not exceed 1%.”

COMPARISON OF RF LEVELS BETWEEN SMART METERS AND OTHER SOURCES

Table 6 gives likely real-world exposure levels to the various sources of RF radiation found in modern dwellings. Since every situation will be different, these take the form of a likely range of values [15].

Source	Frequency	Exposure Level (W/m ²)	Distance	Temporal Characteristic	Spatial Characteristic
Mobile phone	900MHz, 1.8GHz, 2.1GHz	10 to 50	At ear	During call	Highly localized
Cellular base station	900MHz, 1.8GHz, 2.1GHz	0.00005 to 0.02	Tens of metres to a few km	Constant	Relatively uniform
Microwave oven	2.45GHz	~50	5cm	During use	Localized, non-uniform
		0.5 to 2	60cm		
Wireless LAN, WiFi	2.4GHz, 5GHz	0.002 to 0.01	1m	Constant	Localized, non-uniform
Radio/TV broadcast	0.1MHz (long-wave radio) to 800MHz (UHF TV)	0.01 (highest 1% of population) to 0.00005 (50% of population)	Hundreds of metres to tens of km	Constant	Relatively uniform
Smart Meter 0.25W, 1% to 1W, 5%	900MHz, 2.4GHz	0.001 to 0.02	1m	During transmission	Localized, non-uniform
		0.00009 to 0.002	3m		

Table 6. Range of likely personal exposure levels in the home from various RF sources [15]

From these figures it is clear that the maximum likely exposures in the home are due to mobile phone use, particularly if prolonged, and standing right next to the Microwave oven. As stated earlier the standards have special provisions for mobile devices, which have not been discussed here, as they are not relevant to Smart Meters.

OTHER STUDIES

In the USA, where concern over RF radiation from Smart Meters has been expressed for some time, various independent bodies have carried out research in this area [14, 15, 16, 17, 18]. These reports have been studied as part of the production of this white paper, but have not been used as a substitute for investigating the problem from basic principles. [16] shows practically and conclusively that every one of the many meters and installations tested fall well within the FCC MPE limits. In [17] Sage Associates list certain conditions where their computer modelling shows that FCC MPE limits could be exceeded for a body in extremely close proximity to a single meter (less than 15cm), in very close proximity to multiple meters (28cm) and, based on findings from another research group [13], in a steel shipping container (used as a model for a steel lined kitchen) in close proximity to a single meter (71cm). However they also appear to misinterpret the results in [12], which does not enhance the credibility of their findings. In [18] the California council on science and technology concludes:

1. The FCC standard provides a currently accepted factor of safety against known thermally induced health impacts of smart meters and other electronic devices in the same range of RF emissions. Exposure levels from Smart Meters are well below the thresholds for such effects.
2. There is no evidence that additional standards are needed to protect the public from Smart Meters.

SUMMARY AND CONCLUSIONS

Smart meters use one or more RF transceiver in the 900MHz, 1.8GHz or 2.4GHz band. During transmission (normally limited to a maximum of 50% of the time and in practice usually very much less than this), they radiate RF power.

RF radiation causes heating of body tissue. International standards for maximum personal exposure (MPE) for members of the general public, based on reducing the heating effect to 1/50th of the amount shown to cause noticeable effects in laboratory animals, are in force and must be complied with. In NZ the current standard is NZS2772:Part 1: 1999, which is to all intents and purposes identical to other national and international standards.

Smart meters using the 900MHz and 2.4GHz ISM bands must comply with the RF radiation power limits of the NZ SRD GURL (in order to limit interference). **In practice they radiate much less power than this allowance and then for only a small fraction of the time, but even if they radiate the maximum amount, on both bands simultaneously, all the time, and the worst case additive reflection occurs, at any distance greater than 1m from the meter, the exposure is less than 35% of the allowable limit.** This leaves at least 65% of the MPE limit for radiation from all other sources.

Smart meters using the 900MHz or 1.8GHz (or potentially the 2.1GHz) cellular bands transmit using the GPRS network used by mobile phones. They transmit data similar to SMS texts, at the same RF radiation levels as a mobile phone. Because under normal conditions they are much further away from the body than a mobile phone, they result in much lower exposure. **Even if the meter spends half its time transmitting data, in a marginal coverage area, at full power, and the worst case additive reflection occurs, at any distance greater than 1m from the meter, the exposure is less than 28% of the allowable limit.** This leaves at least 72% of the MPE limit for radiation from all other sources.

Taking the advice from NZS2772 to “minimize unnecessary or incidental RF exposure”, a sensible approach is to locate Smart Meters such that the general public are unlikely to spend longer than a few minutes per day at a distance of less than 1m from them. This will ensure that mobile phone use remains, by far, the highest RF exposure source that any individual is likely to be exposed to.

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