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Long range metering systems : VHF or UHF ?		
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SUMMARY:

This white paper analyses pros and cons of low frequency bands (VHF, typically 169MHz) and high frequency bands (UHF, typically 868MHz) for long range metering systems.

DOCUMENT HISTORY

DATE	VERSION	AUTHOR	COMMENT
09/03/10	1A	R.Lacoste / ALCIOM	Initial version
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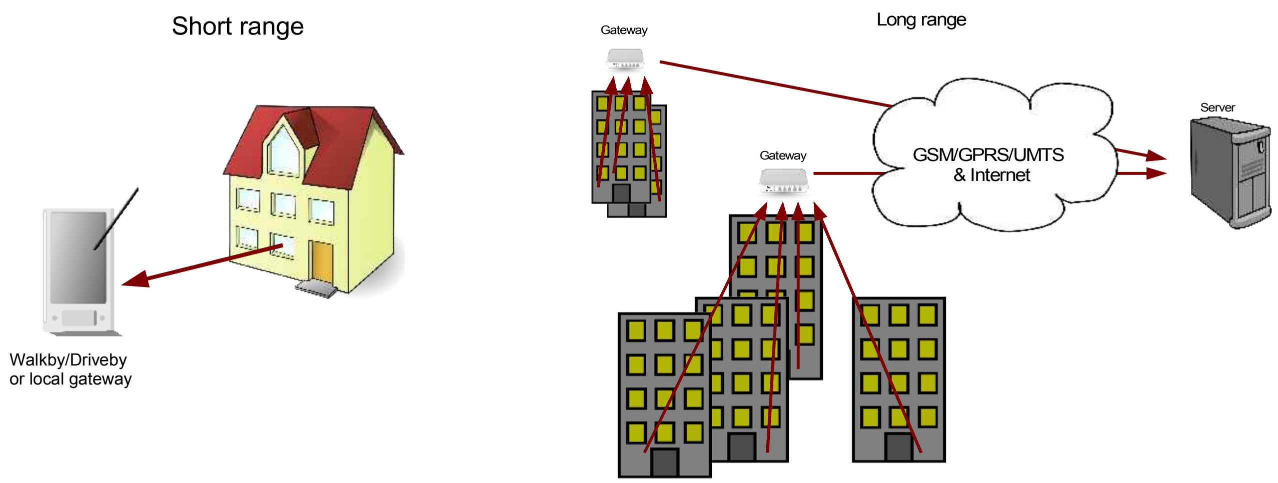
1 Introduction

Metering systems could be split into two distinct application ranges :

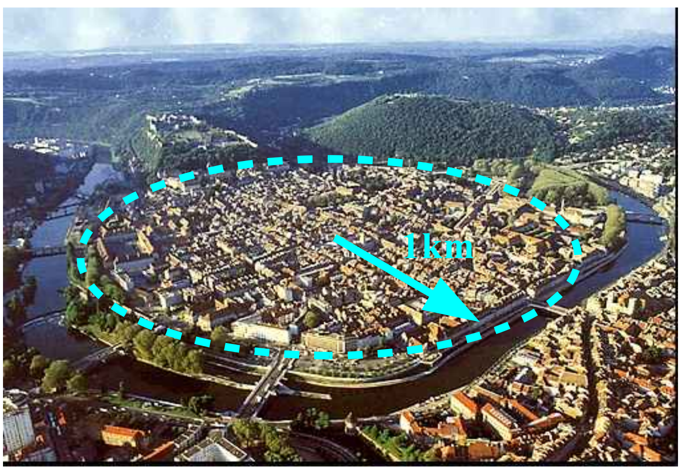
- **Short range metering systems**, in which the useful data (reading of a water, gas or electricity counter, etc) must be transmitted to a closely located receiver. This is typically the case for domestic meter reading. In such systems the data receiver is either a low cost fixed gateway installed for example in corridors, or a moving receiver when using walk-by or drive-by techniques. In both cases the final data transfer to a central server is done through another channel than RF, like Internet.

- **Long range metering systems**, in which the data must be transmitted to a central server through a fixed transmission network. Such long range systems are usually built using relaying techniques, combining low cost RF links to fixed gateways. These gateways are usually installed on roofs, needs external power and are significantly more expensive than short range devices, so their number must be minimized in order to reduce deployment costs.



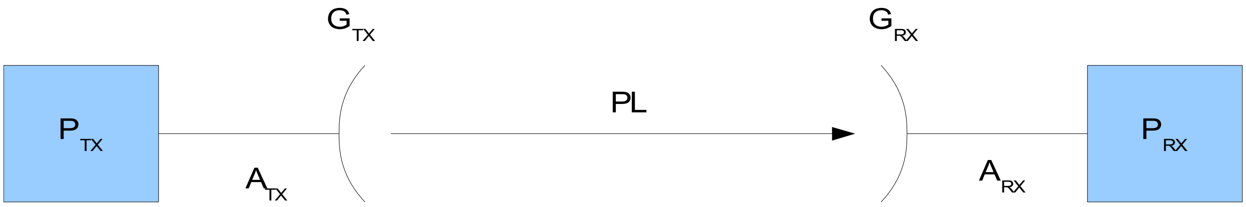
This white paper focuses on long range systems and try to answer to a pragmatic but often misunderstood question : for such systems, **is it better to use a rather low RF carrier frequency (like the 169MHz VHF metering band, ex Ermes band now available through Europe) or a rather high RF frequency, like the 868MHz UHF band ?** Intermediate frequencies like the 315/433MHz bands will not be studied for simplicity but would of course provide intermediate characteristics. Likewise, higher frequency bands like the ubiquitous 2,4GHz band will not be studied as they are usually not an option for long range systems.

The comparison will be made on the example of a small city with a radius of 1km around some central point (here a photo of Besancon just as an illustration...).



2 Some theory first !

Ok, let's start with some theory refresh. The overall link budget of an RF link can be synthesised as follows :



On this diagram :

- P_{TX} is the output power of the transmitter
- A_{TX} is the overall losses on the transmitter side (cable losses, impedance mismatch losses, connectors losses, etc)
- G_{TX} is the gain of the transmitting antenna, as compared to an hypothetical isotropic antenna (0dBi by definition)
- PL is the path loss between both antennas, due to the attenuation of the signal flowing in the air as well as due to all other signal degradation factors (fading, obstacles, polarisation, etc)
- G_{RX} is the gain of the receiving antenna, as compared to an hypothetical isotropic antenna as well
- A_{RX} is the overall losses on the receiver side (cable losses, impedance mismatch losses, connectors losses, etc)
- P_{RX} is the power of the received signal

When using decibels the equation linking all these values is very simple : just add all gains and subtract all losses !

$$P_{RX}=P_{TX}-A_{TX}+G_{TX}-PL+G_{RX}-A_{RX} \quad \text{(equation 1)}$$

The link will be operational as long as the received power P_{RX} is above the sensitivity threshold S_{RX} of the receiver.

In this equation the predominant term in terms of absolute values is by far the path loss PL. A reasonable guess of the path loss can be calculated using the empirical form of the Friis formula, here in dB :

$$PL=32{,}4+20\log\left(\frac{f}{1\mathrm{GHz}}\right)+10\,n\log\left(\frac{d}{1\mathrm{m}}\right) \quad \text{(equation 2)}$$

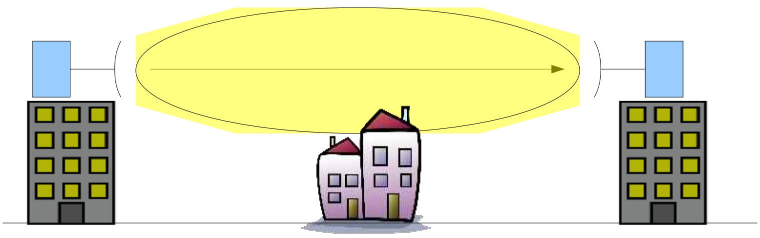
In this formula :

- f is the frequency in GHz
- d is the distance between transmitter and receiver
- n is a number ranging from 2 (free space conditions) to 3 or even 4 in dense indoor environments

More evolved formulas do exist, like the Hata Model for urban areas, but this simplified formula will be enough for this high level analysis. A numerical example will illustrate the high path loss values commonly encountered in RF transmissions : Do the calculation for a 500m link at 868MHz, assuming an optimistic value of 2,2 for n and you will find a 90dB path loss. That means that the power arriving on the receiver antenna will be $10^{90/10}$ or one billion times lower than the power leaving the transmittter antenna...

In real life the signal attenuation could be far higher than the theoretical power, mainly due to the following issues :

- **Signal absorption** will occur when obstacles are present on the signal path, or even close to the straight signal path, more exactly for obstacles that enter the first Fresnel zone between the two antennas :

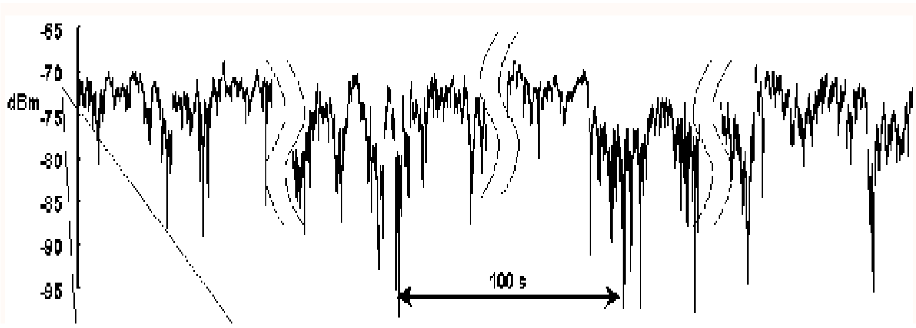


  The radius r (in meter) of the first Fresnel zone for a frequency f (in GHz) and a distance D (in km) between antennas is calculated as :

$$r = 17{,}32\sqrt{\frac{D}{4f}}$$

  So even for a low frequency of 169MHz the radius of the Fresnel zone is a small 21m for a 1km link. So only obstacles on the direct line of sight between antennas are relevant, but would imply a high loss. For example an absorption loss of 15 to 25dB is common for a foundation or brick wall, where as a wood door implies a small attenuation of 3-5dB. These absorptions are of course frequency-dependant : as a common rule absorption due to propagation through objects tends to increase with frequency.

- **Multipath fading**, caused by reflected and direct signals get mixed up and potentially nullifying each other). 20dB fading holes are quite common in “null zones” where signals cancel. The physical size of one of these null zones is roughly proportional to the wavelength.



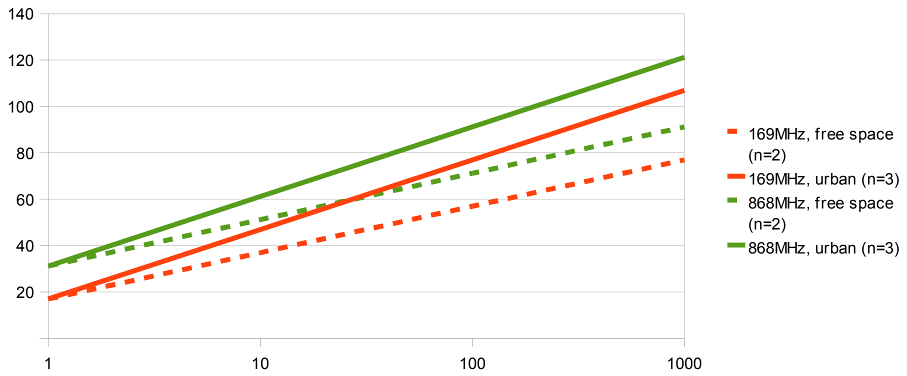
- **Diffraction** is also caused by objects with sharp angles are presents on the signal path, as well as **signal scattering** occurs when small objects, relative to the RF wavelength (L=C/f), are on the signal path. These two parameters are more or less included in the n parameter of the empirical Friis formula given above, but it is important to notice that scattering, for a given small obstacle, will be higher with shorter wavelength, meaning that the attenuation will be higher when the frequency is higher.

- **Polarisation losses** occurs when the polarisation of the receiving and transmitting antennas are not aligned, or when the polarisation plane gets changed through the propagation.

3 Path loss comparisons...

The empirical Friis formula (equation 2) clearly shows that the path loss is directly proportional to frequency : for a given distance, and for a given transmitter and receiver, the path loss will double when the RF carrier frequency doubles. Here under some numerical examples of both free space (n=2) and typical urban (n=3) losses against transmission distance both at 169MHz and at 868MHz :

	Path loss (dB)			
Distance (m)	169MHz, free space (n=2)	169MHz, urban (n=3)	868MHz, free space (n=2)	868MHz, urban (n=3)
1	17	17	31	31
10	37	47	51	61
50	51	68	65	82
100	57	77	71	91
1000	77	107	91	121

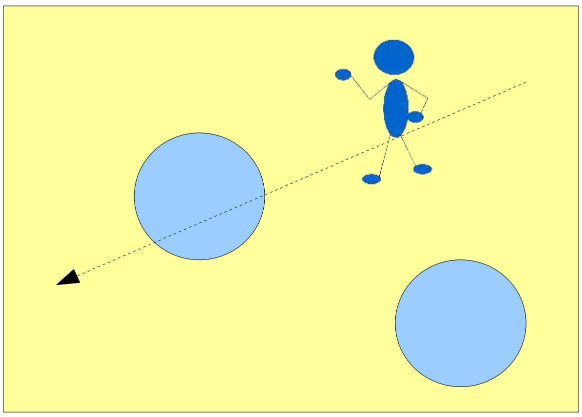


Therefore a 868MHz link will have a path loss 14 dB higher than a 169MHz link, meaning that the received signal power will be 25 times lower, theoretically whatever is the distance and the environment.

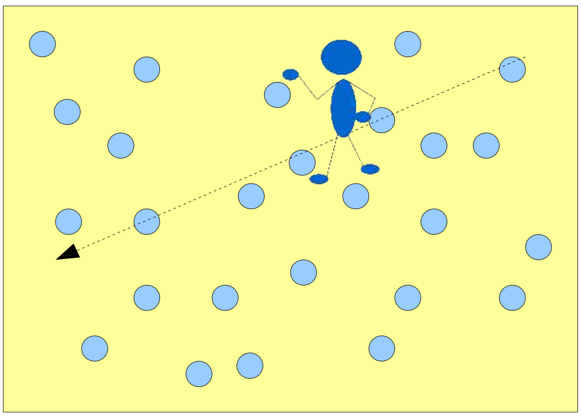
Signal absorption, diffraction and scattering by obstacles will also be higher at 868MHz than at 169MHz : lower frequencies have more capabilities to flow “around objects” or “through objects” (except in specific cases where resonance could happen), as their wavelengths are longer (1,77m for 169MHz against 24,5cm for 868MHz).

There is however **an advantage of the 868MHz in terms of multipath fading** : as the wavelength is smaller at 868MHz then fading nulls will have a smaller dimension in terms of distance. This means that at 868MHz a moving object will enter more often fading nulls, but will also left them quicker, which could give a more satisfactory user experience even if the probability to have a failed transmission at a given place is identical.

169MHz : few multipath reception holes, but large



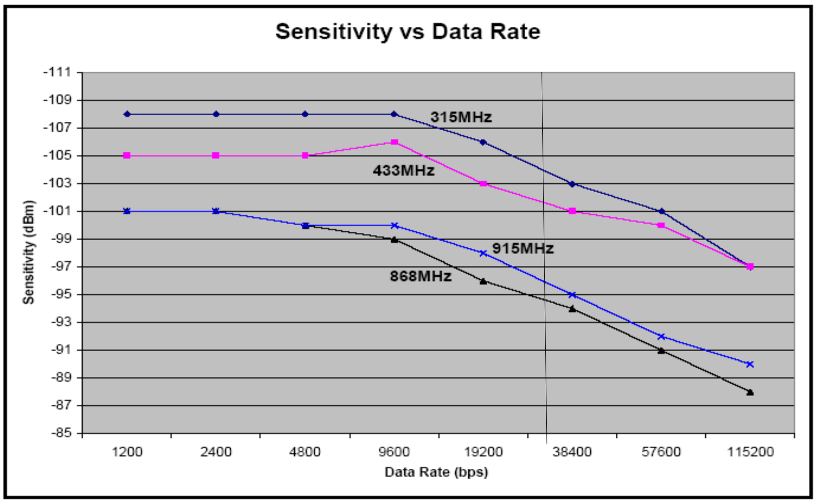
868MHz : a lot of multipath reception holes, but smaller



4 Transmitters and receivers : Same performances ?

Receivers are made of silicon chips, which have their intrinsic limitations. A receiver front-end is an amplifier, and amplifiers have a given (gain x bandwidth) product, higher or lower depending on performances of the chip but roughly constant for a given component. So when the required bandwidth (ie the working frequency) is higher then the gain must be smaller. **That means that, for a given technology, a receiver will always have a higher sensitivity when the frequency is lower.**

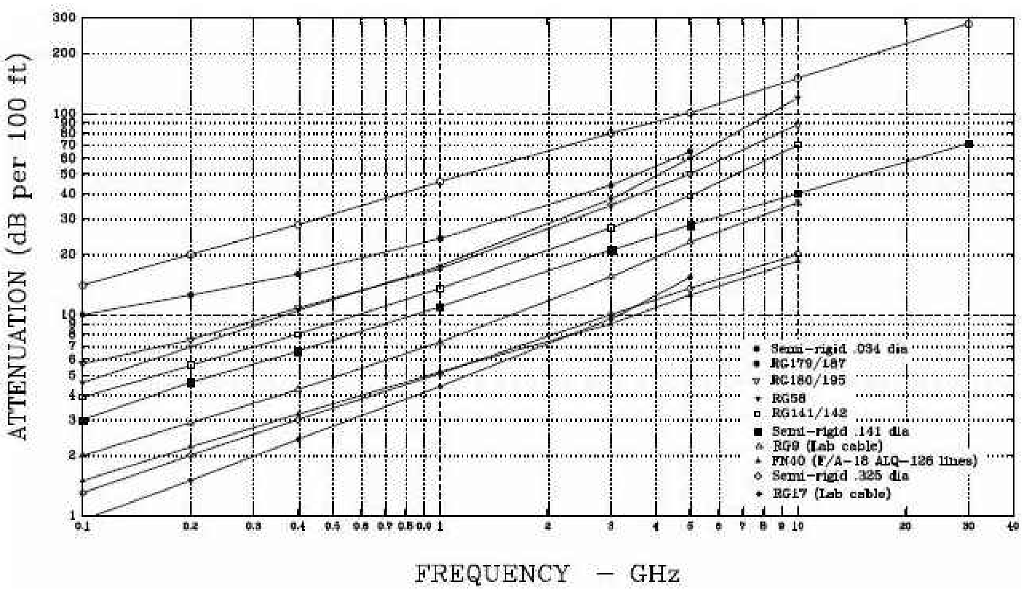
Just as an example here under an extract from the data sheet of the TRC101 UHF transceiver chip from RFM, which clearly shows that the receiver sensitivity decreases with frequency for a given data rate.



With the same technology a 5 to 10dB sensitivity gain at 169MHz as compared to 868MHz will seems reasonable.

Similarly a transmitter will usually require **less electrical power to achieve the same output power at a low frequency than at a high frequency**, for a given technology**.** This is due to the silicon behaviour which implies higher parallel capacitive losses when frequency increases (loss through a given parasitic capacitor is higher when frequency increases), as well as higher gains to compensate these losses.

Lastly cable and connector losses, if any, are higher when the frequency is higher.



At sub-GHZ frequencies the impacts will however be very small as the cables are usually small in metering systems.

5 Bit rate, channel width, and sensitivity

The channel width is usually 12,5KHz at 169MHz (even if the REC7003E european recommendation allows up to 50KHz), but is 25KHz in the 868.4-868.65MHz g3 harmonized band (this is the 868MHz sub-band where a transmit power up to 500mW is allowed).

As the in-channel noise is proportional to the channel bandwidth this means that a 868MHz receiver will get twice more noise than a 169MHz receiver. **If both receivers have the same other performances, if the specified channel width are used and if the bit rates are identical then the 169MHz receiver will get a 3dB improvement in sensitivity** for a given S/N performance, compared to the 868MHz product.

This discussion is very theoretical, as nothing prevent a 868MHz system to use a narrower receiver bandwidth, but existing standards usually comply with these assumptions.

It should be highlighted that a lower bit rate implies a higher S/B performance of the receiver as shown by the Shannon formula :

$$D = W \log_2 (1 + \frac{S}{B})$$ (equation 3)

In this formula D is the channel capacity (bits per second), W is the channel width (in Hz of bandwidth) and S/B is the signal over noise ratio that the receiver is capable to decode. Similarly bit rate is related to overall traffic capacity. However this applies both to 169MHz and 868MHz so this is not a difference.

6 What about antennas efficiency ?

There are two issues linked to antennas : impedance matching and stability to varying environmental conditions. Let's talk about impedance matching first. It can be showed that the lowest obtainable quality factor of an antenna can be approximated by the following formula :

$$Q = \frac{1}{(k\,a)^3} + \frac{1}{k\,a}$$ (equation 4, extended Chu-Wheeler criterion)

If this formula a is the radius of a sphere enclosing the antenna, and k is calculated as :

$$k = \frac{2\pi}{\lambda}$$ (equation 5)

The wavelength at 169MHz is 5 times larger than at 868MHz. Assuming that the space available to fit the antenna is given (meaning that the 169MHz antenna must have roughly the same size than a 868MHz antenna) then the two formulas shows that Q will be significantly higher at 169MHz. For a narrow band antenna Q is simply the frequency divided by the bandwidth of the antenna. **Therefore, for the same physical size, an optimized 169MHz antenna will have a significantly smaller bandwidth than an optimized 868MHz antenna.**

That doesn't mean that it would be impossible to design a small 169MHz antenna as good as a small 868MHz antenna, however that means that the design will be far more difficult to tune in order to get the same performance. It also means that external changes (wiring, proximity of walls, etc) that could detune the antenna will have a stronger effect on a 169MHz antenna. Moreover a small 169MHz antenna will be farer to 50ohm than a 868Mhz antenna of the same size. Therefore the matching network will be more difficult to design and more sensitive to detuning.

In summary a 169MHz antenna is naturally 5 times larger than a 868MHz antenna. If space is constrained, as it is always in metering applications at least on the transmitter side, then the 169MHz antenna will have a smaller bandwidth and will be significantly more sensitive to detuning. **Experimentally a classical short (10/15cm) 868MHz can provide a gain of 0 to 3dBi, whereas it is very challenging to design a 169MHz with the same size with a gain higher than -10 to -5dBi. So, when space is constrained, there is a real life 8 to 12dB advantage for 868MHz.**

7 Near vs far field

The boundary between the radiating near field and far field of an antenna is generally accepted as :

$$M \approx \frac{2\,L^2}{\lambda}$$

With L the largest dimension of the physical antenna, and lambda the wavelength. Assuming an antenna of the same size, say 20cm, for both frequencies, this translates into M=4,5cm at 169MHz and M=23cm at 868MHz. **This means that a 20cm long 868MHz antenna will be significantly perturbed by any objects 23cm around it, whereas a 20cm long 169MHz antenna will only be significantly perturbed in 4,5cm radius.**

Nota : the analysis will be opposite if the antenna size would not be constrained.

8 Cost differences ?

On the technological side medium power transmitters both at 169MHz and 868MHz can be designed around very low cost integrated transceivers. The market for 868MHz chips is far larger so the silicon solutions tend to be cheaper in that frequency band. However as long range metering systems usually require high end transceivers in order to get a level of spurious and phase noise low enough (to allow the addition of a medium power amplifier) the cost difference is quite small : **The cost of a 169MHz-compatible chipset is marginally hgher than the cost of a 868MHz high-power compatible chipset**. Top-range high power systems may require significantly more expensive designs (discrete VCOs, etc) but this is both the case for 868MHz and 169MHz. Moreover 868MHz RF power amplifiers are more costly than 169MHz amplifiers.

However as the 169MHz channels are smaller this usually requires a higher precision reference oscillator, implying an extra cost.

In summary 169MHz transceivers are slightly more expensive than 868MHz systems, but more linked to smaller market size than actual technical reasons.

9 A short synthesis

The following table synthesizes the pros and cons of both frequency bands in terms of RF engineering :

Factor	169MHz	868MHz
Path loss	14dB better than 868MHz	14dB worst than 169MHz
Absorption by obstacles	Lower as frequency is lower	Higher as frequency is higher
Scattering and diffraction	Better as wavelength is long	Worst as wavelength is short
Multipath fading	Few, but large null holes (could be mitigated by antenna diversity)	Numerous, but small null holes
Intrinsic receiver sensitivity	5-10dB higher as GBW limited	5-10dB lower as GBW limited
Cable a connectors losses	Very low	Low, as cables are small anyway
Transmitter efficiency	Higher efficiency (low capacitive losses)	Lower efficiency (high capacitive losses)
Receiver sensivity	3 dB higher as channel width 12,5KHz	3dB lower as channel width 25KHz
Antenna efficiency	8-12dB worst for a small size antenna	8-12dB better for a small size antenna
Antenna perturbing zone	Small (for a fixed size antenna)	Larger (for a fixed size antenna)
Cost	Slightly higher today	Slightly lower, as marker size larger

In summary a 169MHz link would provide an average 14+7+3-10=14dB better link budget than a comparable 868MHz link, even assuming that the antennas are constrained to have the same physical size. **So, with the same transmit power, a 169MHz system would provide a five-times increase RF coverage as compared to 868MHz in open field conditions, and up to a three times increase in typical urban propagation (n=3).**

Let's take a numerical example with a small city of 1km radius. Assumptions :

- Transmit power 500mW
- Antenna gain, meter side : -10dBi at 169MHz, 0dBi at 868MHz. Antenna gain, receiver side : 0dBi for both
- Packaging and other losses : 4dB on meter side, 1dB on receiver side
- Damping factor : 2,5 (light urban condition)
- Fading margin : 7,5dB
- Polarisation loss : 3dB
- Building penetration loss : 25dB at 169MHz, 30dB at 868MHz
- Overall receiver sensitivity : -120dBm at 169MHz, -110dBm at 868MHz

The calculated link budgets are then the following :

LINK BUDGET V2

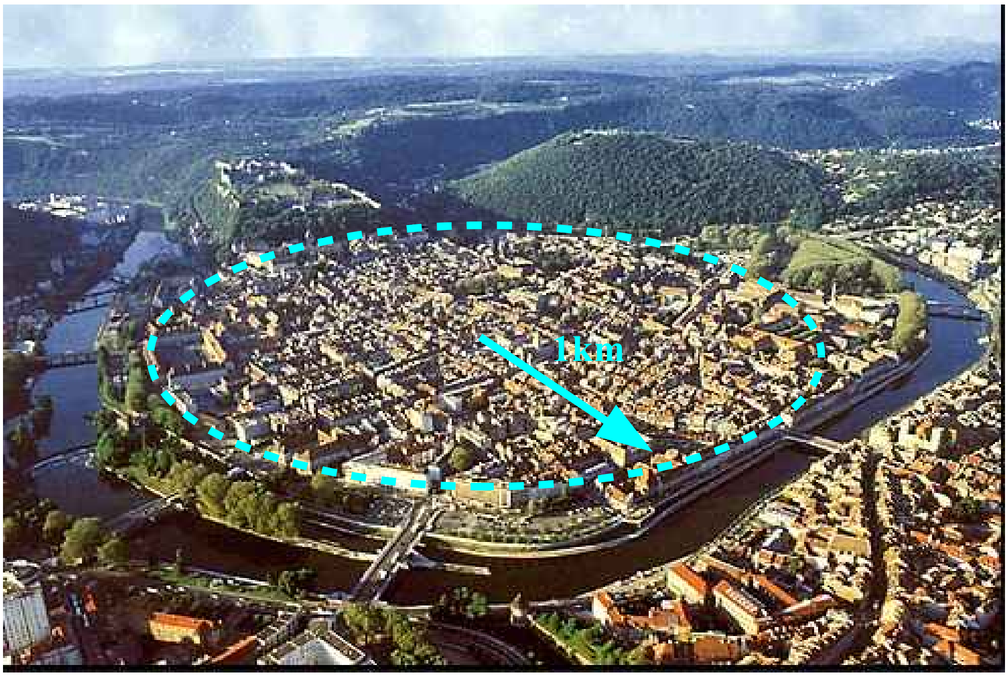
Transmitter		
Output power	27	dBm
Or	501,19	mW
Frequency	169	MHz
Cabling and connector losses	1	dB
TX antenna gain	-10	dBi
Packaging losses	3	dB
Transmitted power	13	dBm
Path		
Distance	1000	m
Damping factor - Free space: 2 - Shops : 2,2 - Offices, light walls : 2,6 - Hard walls : 3	2,5	(2 à 3)
Floors crossed	0	(0 à 3)
Fast fading margin	7,5	dB
Polarisation loss	3	dB
Buildig penetration loss	25	dB
Free space loss	**127,46**	dB
Receiver		
Received power	-114,46	dBm
Packaging losses	0	dB
RX antenna gain	0	dBi
Cabling and connector losses	1	dB
Net power	-115,46	dBm
RX sensitivity @ BER=1%	-120	dBm
Link budget	**+4,54**	**dB**

LINK BUDGET V2

Transmitter		
Output power	27	dBm
Or	501,19	mW
Frequency	868	MHz
Cabling and connector losses	1	dB
TX antenna gain	0	dBi
Packaging losses	3	dB
Transmitted power	23	dBm
Path		
Distance	200	m
Damping factor - Free space: 2 - Shops : 2,2 - Offices, light walls : 2,6 - Hard walls : 3	2,5	(2 à 3)
Floors crossed	0	(0 à 3)
Fast fading margin	7,5	dB
Polarisation loss	3	dB
Buildig penetration loss	30	dB
Free space loss	**129,20**	dB
Receiver		
Received power	-106,20	dBm
Packaging losses	0	dB
RX antenna gain	0	dBi
Cabling and connector losses	1	dB
Net power	-107,20	dBm
RX sensitivity @ BER=1%	-110	dBm
Link budget	**+2,80**	**dB**

With these assumptions the calculation at 169MHz (left) shows that the full city, ie 1000m range, can be covered with a single centrally located receiver and with a reasonable 4,54dB margin. However at 868Mhz a positive link budget can only be achieved with a link distance reduced down to 200m (giving a +2,80dB margin).

So this small 1km-radius city would require only one central gateway at 169MHz, but around 8 to 10 gateways or repeaters at 868MHz :



169MHz : 1km radius per receiver

868MHz : 200m radius per receiver

The main downsides of 169MHz are 1/ technically is a more complex antenna design, and 2/ economically a slightly higher unit cost due to a lower demand. However we are convinced that these two facts will be only temporary.