One future for amateur radio?

Part one of an extrapolation on the after dinner talk given at the RSGB Centenary Celebration Dinner in July 2013

GENESIS. At the age of 11 years old, my introduction to the world of electronics and technology began with the construction of a Morse lamp and continued on to a thorough investigation of batteries, lights, switches, volts, amps and watts. Although I was relatively clueless, I was reasonably successful in getting things to work and rapidly migrated to a crystal set and spark transmitter. A period of trying to repair old radios was followed by stripping down of one chassis after another for valuable parts.

By the age of 15 I was exploiting WWII military surplus equipment purchased by the crate on the back of delivering daily newspapers. I had also learned Morse code, built a few crude transmitters, and gained the callsign G3RVC. More importantly, I was becoming 'green fingered', capable of repairing radios and TVs and was also employed in an electrical shop every Saturday. Here I worked for parts, for knowledge, wisdom, and the help of a kindly amateur of extended years.

I avidly read books and magazines on everything electronic, built hi-fi equipment, radio controlled aircraft, receivers and transmitters with whatever components came to hand. But I knew that I understood virtually nothing. So I enrolled at night school, got a job with the GPO Telephones (now BT) and entered industry without a single academic qualification. The next 5 years saw my understanding and skills accelerate as a qualified technician in telephone exchanges, repeater and microwave radio stations. I was also an amateur with ambitions to push the boundaries of what was possible.

At age 19 I decided to design and build my own hybrid transistor-valve HF SSB transceiver. As I recall the AF115/6/7 transistors had an f_t of ~120MHz, whilst the 6VC driver and 2 x QQV06-40A PA tubes were an engineering challenge. Did it all work? Oh yes! It was a masterpiece of ignorance and design plagiarism, and perhaps saw me at a peak of what I was capable of without a fuller education. But I moved up to 2m, built a couple of rigs and became increasingly frustrated at my lack of deep knowledge, test equipment, and the wasted hours getting the seemingly simple to work.

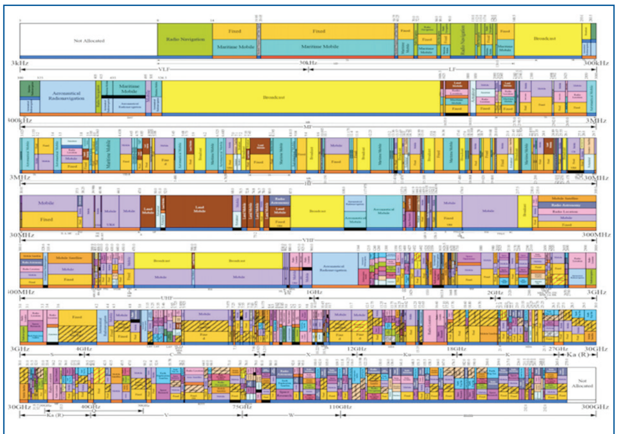

FIGURE 1: Ofcom frequency allocations for the UK.

Almost by accident I stumbled into university having realised that my amateur apprenticeship was over and I needed to get professional, get deep into the technology, and grasp a fuller understanding. And so 5 years at Trent Polytechnic in Nottingham was followed by a further 5 years at Essex University studying engineering, telecommunications, digital transmission, optical and complex systems. During this time I was engaged by BT Labs at Martlesham Heath where I enjoyed an augmented and very different education designing circuits, systems and networks, building test equipment and writing software. I assumed increasing levels of responsibility and understanding to eventually leave in 2000 after being Head of Research and CTO.

Throughout all this I was educated, trained, nurtured and worked with some of the most brilliant minds on the planet distributed throughout the developed world and, as I progressed, I gained a wider view and a more holistic stance. In all of this, amateur radio was my springboard into knowledge, a career and an education that still goes on today. I have also found that this path, this training and my green fingeredness is also common to many of my peer group in industry. We came into the field playing and ended up as capable professionals, and the key element was curiosity, enquiry, experimentation, pushing the boundary of what might be possible, and daring to challenge established wisdoms and practices.

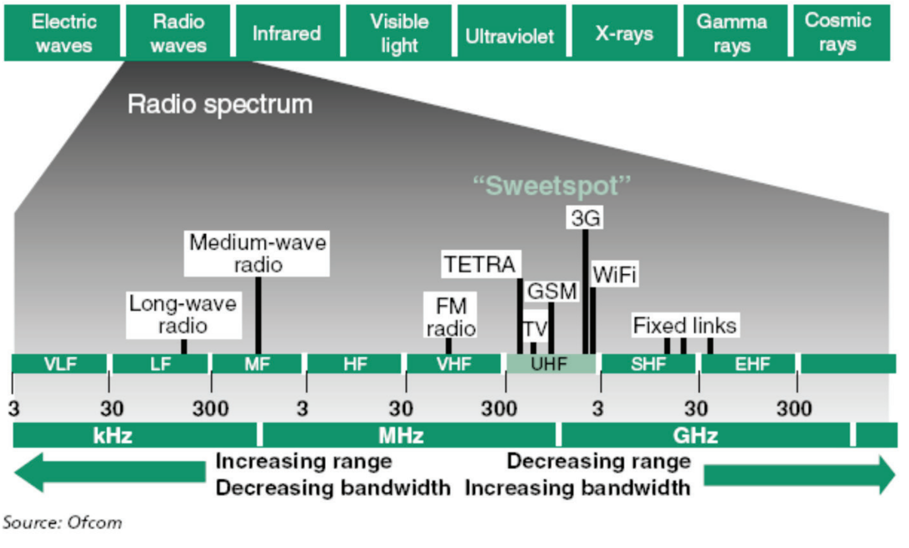

FIGURE 2: The mostly and unoccupied EM spectrum.

AWAKENING. At 22 years old I closed down my shack, sold and/or gave away everything to do with amateur radio. I needed to focus, I needed to concentrate. I was the kid in class with the worst possible education and was going to have to work hard. So I was out of the amateur world, possibly for good, but every few years I would look in on a friend, pick up a magazine, scan the bands and have a listen. Most recently I visited the RSGB National Radio Centre at Bletchley Park as a guest and after dinner speaker at the Centenary Dinner.

To say the least it was an interesting day and another increment in my perception of

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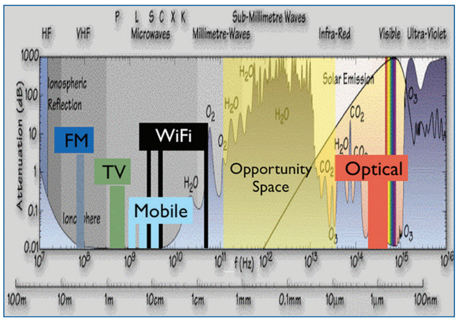

FIGURE 3: The opportunity space above 30GHz.

amateur radio migration. It was as if I had been catapulted back to 1968 when I was 22 years old. The activities and language hadn't changed, but the equipment was certainly far more sophisticated. Chatting to distant contacts on the HF bands using SSB and Yagi antenna. Yep, that's what I was doing when I pulled the plug and moved on.

Sadly, there was no 'homebrew' kit in evidence and everything looked manufactured and expensive, even the antennas. I know there are those working on moonbounce, satellite, ~60GHz, optical free space and new modulation and coding systems, because I meet them in the USA and UK, but they are very much in the minority. But even these groups appear to be on the 'back foot' compared to industry and academia, and worst of all they continue on the near-insane quest of getting more and more information into narrower and narrower bands over longer and longer distances. Haven't they heard that bandwidth is free and distance is now irrelevant?

Amateur radio has a wonderful and valuable history of innovation, exploration and leading the field. Daring to go where the professionals very often would not, but I would suggest that it has largely lost that thread and is being 'dumbed down' to no more than CB radio on afterburners. What does it now take to get an amateur licence? Technical understanding no longer seems to be necessary or indeed the Morse test. For sure buying expensive kit and talking to people in distant lands via whatever mechanism is fun, but there has to be more. The mobile phone, internet, VOIP and Skype actually provide far better and more reliable alternatives if that is all you want to do, and there is no mystery in HF, VHF, SHF, FM, DSB, SSB et al!

The membership of the amateur fraternity is getting visibly older fast and the hobby is failing to attract the young. If we lose the desire to explore, if we lose the young, it is only a matter of time before we lose the hobby and then we will have lost a potentially valuable training ground. Any place, space, and community where people can engage, play, learn and augment there education with practical experiences in areas hard to come by in academia and industry should be coveted. Alarmingly, I now meet newly graduated radio engineers who know nothing of Maxwell's equations, propagation, antennas, intermodulation distortion, or information theory. Their expertise lies in the direction of coding and protocols, and what lies below them in the technology stack is taken as a given. Someone else 'does' and understands the hardware – don't they?

So my central thesis for what you are about to read is as follows:

- Amateur radio is on a trajectory to total stagnation
- A valuable training ground is in danger of being lost
- The exploratory nature of the hobby has to be resurrected
- Pushing the boundary of what is physically possible is vital to the amateur future
- To boldly go where others have not been, or fear to go, is a fundamental amateur credo.

BREAKING THE STASIS. Telegraphy, telephony, broadcast radio and TV, microwave radio, satellite and digital systems have a development and migration path spanning >100 years that remains essentially analogue. Systems and network rationale still labours under the old thinking that bandwidth use should be minimised, distance is the ultimate challenge, connectivity and time are big commercial opportunities. Wrong on all counts! Even our digital systems look like their analogue forbears disguised by 2, 3, 4… 256… discrete signal states instead of a signal continuum.

So let's start by taking an entirely different perspective by pretending that there was no radio past and we only just discovered electromagnetic propagation. Would we invoke a 'band structure' to allocate channels and bandwidth limits? I think not! That technology sprang from the need to create acceptable degrees of orthogonality (signal energy separation if you will) around 1915 as we transited from spark to oscillator, from Morse key to microphone, from wire to wireless.

What might we do instead? How about achieving signal separation by the use of codes? And how about spreading energy across the entire radio spectrum and operating under the thermal noise instead of concentrating energy in narrow bands with the subsequent interference, intermodulation and non-linear design problems? And how about using 'just enough energy to communicate' rather than 10, 100 or even 1000 fold more than absolutely necessary? Digital can do all this and much more if we abandon the old ways, the old thinking, and dare to embrace the new technologies, opportunities and thinking.

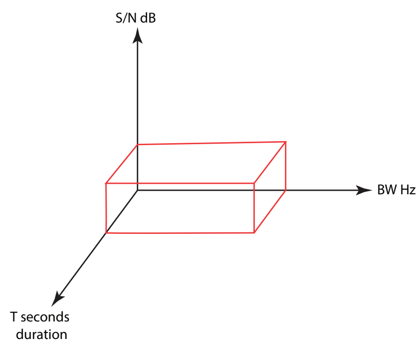

FIGURE 4: Information transmitted over a channel expressed as a volumetric function of S/N, BW and Time.

EXISTENCE THEOREM. In 1976 I attended a NATO workshop where INTELSAT revealed that they had noticed the noise floor on all their analogue satellite transponders progressively creeping up above the thermal and cosmic base level. Someone, or some organisation, was hijacking their satellites and communicating for free courtesy of their open 20MHz bandwidth transponder channels. They didn't know who, how, or where from! But a good guess would have been some government agency, using spread spectrum, for embassies and/or military purposes.

At the time, spread spectrum equipment and information coding systems demanded computing power that might consume a room. It had all been in use by the military since about 1947 and had remained on the 'secret list' for decades but, in 1979, it was in the open and being studied throughout academia. Today, spread spectrum is used for mobile phones and data communications on a routine basis, but it is confined to relatively narrow band (analogue bands) and a lot of the spread and capacity advantage is lost. In addition, the inevitable guard bands between operators, co-located devices and limited spectrum allocations don't help the situation either.

THE CROWDED SPECTRUM – NOT! Looking at the FCC and Ofcom frequency allocations, it is very easy to gain the view that the radio spectrum is over used and bandwidth is in short supply, **Figure 1**. In reality, the most dense radio locations we have – cities – seldom reach 17% usage. The detail is amplified if we analyse 'bits moved' versus capacity actually available. Then we get a very different picture that is ever more revealing by town, village and sparsely populated areas. In short, we have an abundance of bandwidth that remains unused! We also have cellular structures that can be engineered smaller and smaller to effectively release an infinity of bandwidth.

Abandoning band and channel structure and moving to an 'available by energy density model' would go a long way to solving this problem, especially when we add a cognitive and configuration programmable element too. The scale of the opportunity to hand is made obvious in **Figures 2** and **3**. But there is much more! The world has migrated from a few hundred big transmitters with thousand of receivers operating over vast distances to billions of transmitters operating over short distances spanning a few metres to a kilometre or two. For example; the last count I found that my household owned over 85 transmitters spanning car keys, remote controls, door bells, mobile, pads, laptops, Wi-Fi hubs, hearing aids and more.

Today, we have 6 billion people with mobile phones; around 4 billion with access to a PC and 2 billion with access to at least 2 or 3 mobile and computing devices. Then, of course, we have 'The Internet of Things' building fast with a forecast 50 – 200 billion devices expected to enter the market over the next decade and, of course, an ever expanding number of Cloud networks. The outcome over next decade or two is obvious – more and more signal space (bandwidth) will be demanded and short distance operations will dominate.

So it really is time for us to think and act differently. Where does amateur radio fit in, where will it be making a contribution and will it be able to hang on to valuable bands in a mobile and machine dominated future? In short; where is the value, the exploration and the contribution?

THE INFORMATION SPACE. At this point it is worth standing back and asking what it is we are actually trying to do, and I would posit the following:

- *"Our mission is the maximal exploitation of the Electromagnetic Spectrum to the advantage of Man and Machine for the purposes of communication, sensing, manipulation, and processing*
- *"And in doing this we should be prepared to exploit the 'spectrum space' to best advantage including performance, sustainability and longevity."*

In the arena of telecommunications, networking and information this boils down to enabling and supporting the maximal number of entities to communicate and work reliably with a given quality of service and minimum interference, at the lowest possible cost in terms of money, energy, time and materials.

Fortunately, our forebears include people like Claud E Shannon (American mathematician, engineer and cryptographer) and Ralph V L Hartley (engineer and electronics researcher), who derived the fundamentals of information theory during WWII. This culminated in a classic paper

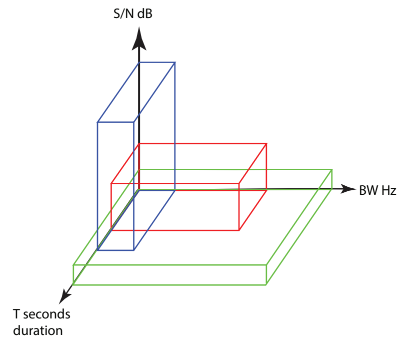

FIGURE 5: The same information transmitted over a channel in three different modes using S/N, BW and T and variable factors.

published by Shannon in 1948 whilst at Bell Labs where he used an entirely entropic descriptor. Here the upper bound capacity of any channel of a given bandwidth 'B' subject to additive noise power 'N' and signal power 'S' is given by:

$$C = B \log_2(1 + S/N) \qquad \text{(equation 1)}$$

where:
C = channel capacity in bit/s
B = bandwidth in Hz
S = average received signal power over the bandwidth in watts
N = average noise or interference power over the bandwidth in watts
S/N = linear signal to noise ratio or carrier to noise ratio for Gaussian noise

In any given time period the information transfer via the channel is simply stated as:

$$I = BT \log_2(1 + S/N) \qquad \text{(equation 2)}$$

It is worth noting that all this has since been extended way beyond the assumed Gaussian channels and white noise to include more general situations embracing all the known culprits of interference and channel/signal degradation. But for our purposes equation 2 is sufficient to communicate the principles of our argument.

However, there is one minor change to equation 1 and equation 2 we should, record, and that is the inclusion of a factor 'k' to account for the nuances of any given practical system – ie practical systems are never as good as the theoretical! The formulaic modification is trivial but a useful 'reminder of reality' and the most generally form of the equations quoted in publications and discussions. Therefore, (equation 2) becomes

$$C = B.T \log_2(1 + k.S/N) \qquad \text{(equation 3)}$$

where k is a constant.

In **Figure 4** we graph equation 3 to reveal its most important characteristics, but in doing so we have taken a number of justifiable engineering liberties. In order of operation we have:

1. Assumed that k.S/N >> 1 so $\log_2(1 + k.S/N) \sim \log_2(k.S/N)$
2. We have the applied a conversion from log base 2 to log base 10
3. We have then multiplied by 10 to achieve a dB descriptor
4. Finally, we apply a factor K to take care of the transformation above and the loss of k

Hence our approximation to equation 3 looks like this:

$$C \sim B.T.K.S/N_{dB} \qquad \text{(equation 4)}$$

Whilst this is a 'gross approximation and distortion of the truth' in the general case, and should be remembered as being such, it is a powerful way of understanding many of the basics we are trying to exercise on the journey of our general mission.

What we now see is information as a volumetric quality with axes B, T and K.S/N, and we can trade these quantities to advantage as depicted in **Figure 5**. This being the case opens the book on spread spectrum and the trade-off between the variables to hand. That is; we can drive down power by expending bandwidth and or time and vice versa.

For data transmission we enjoy the freedom of data speed up or slow down – ie 'T' is a variable, but for the real time communication of speech, vision or artificial reality etc, then time is real and option T cannot be easily exercised.

At this point we can contemplate turning the established norms upside down and instead of conserving bandwidth by trying to squeeze more and more information down narrower and narrower pipes (channels if you will), let's do the opposite. For example; human speech might be transmitted over a radio channel of 2.5kHz at a S/N of 30dB, but suppose we spread the speech energy over 25MHz? Then we would only need a S/N of 0dB. And should we spread over 2.5GHz, a S/N of -30dB would suffice. So we are now operating at or well under the thermal noise level and invisible to all other users.

We have now outlined the core of our argument. Bands and channels are man made and not the diktat of some deity or even fundamental to the laws of physics. It has all been a pure engineering convenience; we arrived here because it was all possible with the technology of the time. In Part 2 we will examine the technology and some of the understanding available today that says there is an alternative, a new and better way, and one in which the amateur radio fraternity not only need to engage, they have the opportunity to take a lead position, to bravely go where no…

One future for amateur radio?

The concluding part of an extrapolation on the after dinner talk given at the RSGB Centenary Celebration Dinner in July 2013

SPREAD SPECTRUM (SS). During wartime it is vital that the enemy is unable to intercept any form of communication. Codes, cyphers and encryption sprang from that need, and reached its first electronic zenith during WWII. Enigma is probably the most important and visible from that era, but at the same time secure analogue speech transmission was realised using channel parsing and rearrangement on undersea cables and HF radio channels, see **Figure 6**. At the time a room full of equipment was necessary to provide even a modest amount of speech security – with even more for any enemy intent on cracking such systems. Of course, today we could do so on a reasonably modest laptop!

On another dimension you don't want an enemy to locate any of your facilities via their emissions, nor do you want your signals jammed. So there is a need for security, invisibility, anti-jamming and, hopefully, a resistance to all forms of interference. If you can 'communicate in the noise', the first three are assured and the fourth might just be a side benefit! We might never know the full history of how, who, where and exactly when theoretical and practical studies started, but we know it was during the early 1940s, and practical systems have been in use since the 1950s. And, of course, today, every mobile phone uses spread spectrum (SS), although in a relatively narrow band mode and certainly not with invisible signals – they are well clear of the noise. In this context SS is employed to improve traffic density squeezing more out of spectrum 'slots' sold by governments at a very high premium.

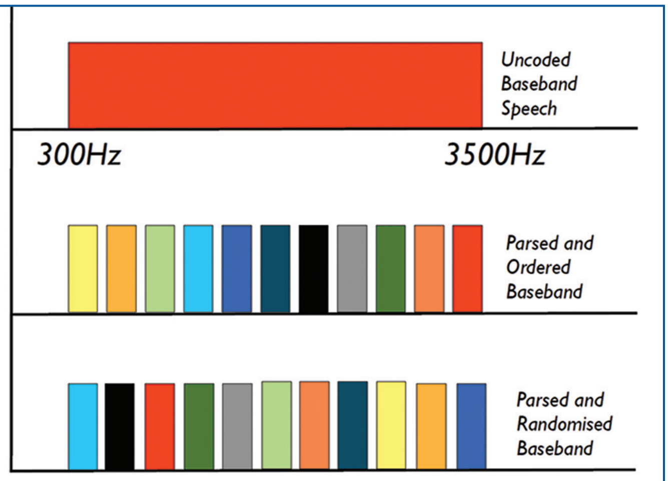

FIGURE 6: WWII Speech coding using channel frequency parsing, random sideband inversion and re-arrangement.

GOING BACK TO BASICS. The first thoughts on SS involved standard DSB and SSB channels with step changes in their carrier frequency at regular or irregular intervals. Known as 'frequency hopping', security is assured by only the sender and intended receiver being aware of the hop sequence. Systems of this type are still in use today and the basic mode is visualised in **Figure 7**. A slightly more deviant version is depicted in **Figure 8** for single-sideband suppressed-carrier (SSB-SC) with variable timings. On the upside, such systems are easy to design and engineer and with the addition of modest intelligence they can avoid occupied channels, minimise interference and squeeze more 'conversations' into a given bandwidth. On the downside they are not immune to collisions, do not use minimal energy and create a 'noisy' spectrum. They also fall far short of the Shannon capacity ideal [2].

Frequency hopping was successful, if limited, and born of the time and available technology that was a hybrid of analogue/digital engineering. Digital circuitry and computing abilities were crude, scarce and expensive, and realisation was big, heavy and power hungry compared to today. In the 1950s, solutions didn't come on a chip: they came on a rack or a room full of racks! But later down the line spectrum spreading became practicable on a large scale at low cost. Whilst the theory had been established decades before and transistor based demonstrators/systems were built, they only

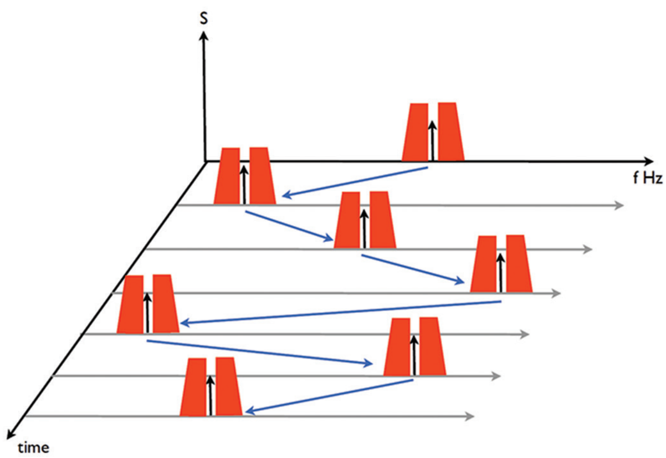

FIGURE 7: Frequency hopping spread spectrum – 'catch me if you can'.

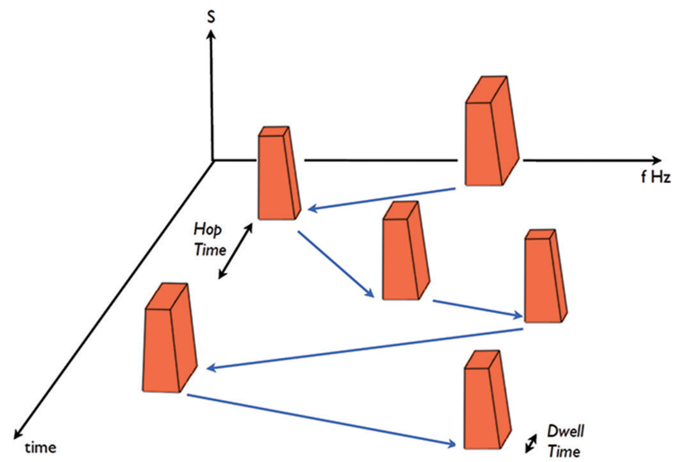

FIGURE 8: Frequency hopping variable dwell and hop time SSB-SC spread spectrum.

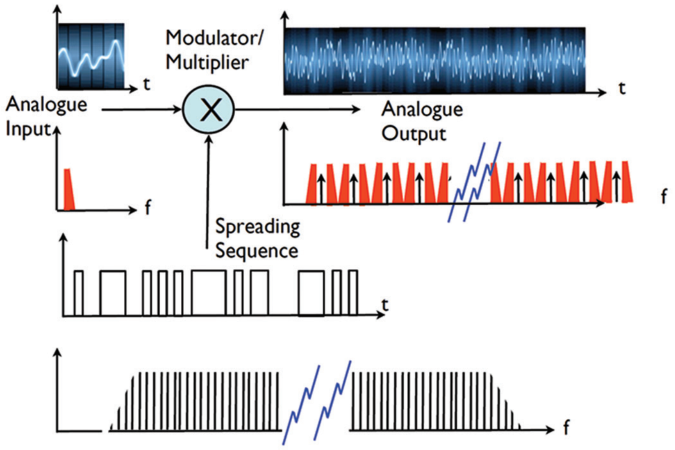

FIGURE 9: Frequency spreading analogue SSB.

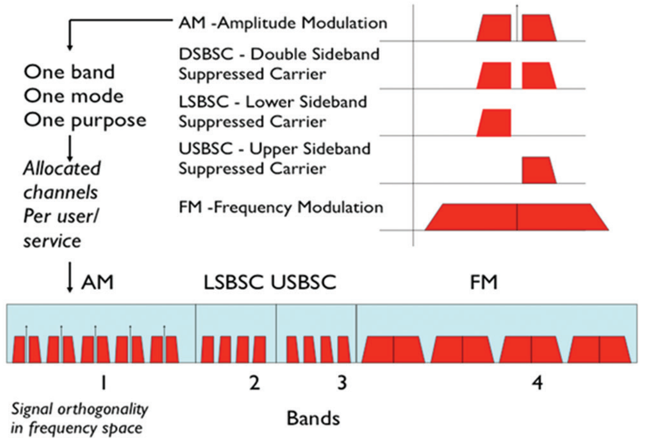

FIGURE 10: The outmoded and largely dying past of analogue transmission in distinct and defended bands.

became practicable on a large scale with the arrival of the integrated circuit. And I am going to suggest that this is where we (amateurs) should focus – at least initially!

SEQUENCE SPREAD SPECTRUM (SSS).

The first spreading systems were no more than voice transmitted in parallel over thousands or millions of carriers, as depicted in **Figure 9**. This type of modulation-demodulation (modem) system is very easy to build, but introduces some interesting engineering challenges:

1 How do you choose a suitable spreading code?
2 How do you communicate and sync the spreading code?

As might be expected, there are a multiplicity of solutions and answers. As a general rule a 'maximally flat' and even energy spread is best achieved by some pseudo-random sequence, or 'M-code'. The code synchronisation at transmitter and receiver usually entails some form of prior knowledge and/or training sequence that has been agreed and designed in from the start.

Putting these subtleties aside for the moment, let us return to the core proposition and how it works and the realisation of benefits. First of all we assume that the future modes of primary interest are dominantly digital. In the world of communication analogue transmission and communication now accounts for <0.1% of the global traffic and is a dying mode by percentage year on year. Second; we are going to assume no bands of any form and focus on the EM spectrum as an open facility that is free to all, see *Figure 10*. Third; we assume that all communication will entail sufficient energy but no more. Fourth; we intend all communication to be below the thermal noise level and thereby invisible to anyone scanning the spectrum. Fifth; our key objective is maximal throughput and minimal interference.

How we might design a system is depicted in *Figure 11*. Here the apparent schematic simplicity belies the subtleties of the process. We should note that the line spectrum of the coding sequence actually 'wraps around' the frequency axis as the phase angle is not a constant at both the transmitter and receiver, and when in synchrony they both match up to give the max demodulated power through voltage addition of the thousands of individual 'carriers'. In contrast, the noise component around each line is uncorrelated and accumulates as a 'power sum' on demodulation. So:

the total demodulated signal voltage $\propto n.v_s$, where
n = the number of decoded components and
v_s = the voltage of each spectral line recovered

whilst the total demodulated noise voltage $\propto n^{1/2}.v_n$
and v_n = the average noise voltage surrounding each spectral line recovered.

So the resulting signal to noise ratio power can be stated as $\propto (n.v_s)^2 / n.v_s^2$

Thus the decoded S/N $\propto n$ (equation 5)

In dB terms this translates to a spread advantage of
$A = 10 \log_{10}(n)$ (equation 6)

So what does this mean? If we take a channel of 3kHz and spread it over 300kHz our spread advantage is $10 \log_{10}(300\text{kHz}/3\text{kHz}) = 10 \log_{10}(100) = 20\text{dB}$, whilst a spread over 30MHz would see a spread advantage of 40dB.

Of course, sequence spread spectrum (SSS) offers further subtleties and advantages that fall outside the scope of this article, but it doesn't take a lot of imagination to see the advantages in terms of interference rejection from conventional analogue and digital signals of a more 'discrete' nature – *Figure 12*.

THE OPPORTUNITY SPACE. Amateur activities already span short, medium and long range communication, but almost all the activities are concerned with narrow band modes. And it has been that way for about ten decades with an almost myopic dedication to a 'furthest and narrowest is best' ethos. At the same time the professionals have moved on to smaller 'cells' for mobile and fixed – 3G, 4G, BlueTooth, Wi-Fi and WiMax et al, see *Figure 13*. There is also a migration underway from broadcast radio and TV as we know it to optical fibre and mobile distribution. These are the demands and markets, along with government agencies and military that have powered the revolution in radio and telecommunication

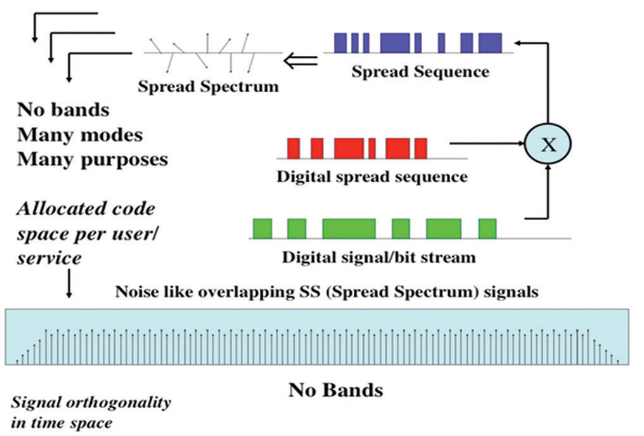

FIGURE 11: How a digital future without bands employing sequence spreading might look.

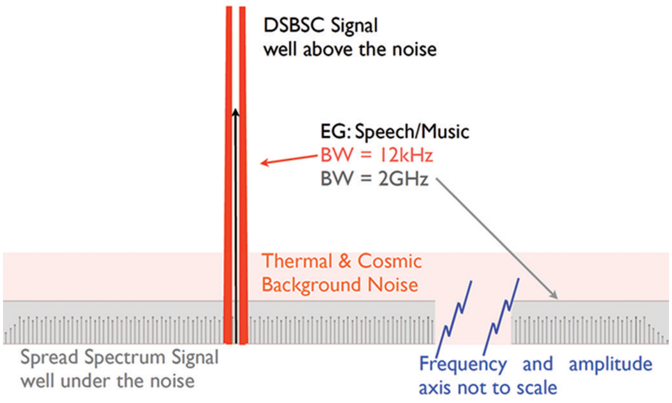

FIGURE 12: An interfering DSBSC signal creating a minimal interference threat.

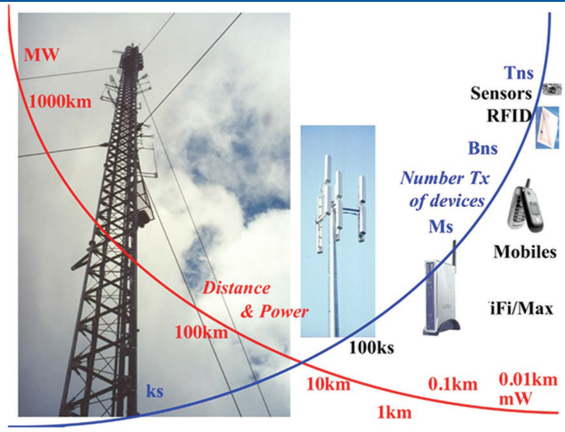

FIGURE 13: Radio History - from 'The Fork Lift Macro' to the 'Ubiquitous Micro'.

developments over the past 50 years. And it is hard to see anything significant contributed by the amateur community apart from a slowing stream of green fingered would-be professionals!

So where should we explore, where should we be going, where does the real novelty lie? The list is endless and the opportunity space vast and exciting. Here is a short 'To Do List' of prospective challenges and opportunities:

1 Signals that span occupy 10 to 100GHz or even more are not trivial to create or detect
2 Likewise efficient antennas for such bandwidth spreads
3 Ditto circuit design and equipment construction
4 Electronic devices will be a challenge and may or may not be easy to come by
5 Efficient signalling protocols may or may not exist already… *but probably not*
6 Efficient synchronisation protocols may or may not exist already… *but probably not*
7 +++

GOVERNMENT + REGULATION + OFCOM. Government and regulation, controls and limitations have been a part of the 'wireless scene' since the early days and bodies like the CCITT and ITU have played a central role in coordinating and guiding country allocations and operating restrictions. Obviously, with a shared resource that spans the planet, coordination of this kind is a necessary evil. Governments, on the other hand, have generally taken a controlist or censorial view that has seen constraints on what can be transmitted and communicated – ie UK pirate radio and pop music in the 1960/70s, CB radio and walkie talkies in the 1970/80s. But from the outset of the mobility revolution they have often taken a commercial line with bandwidth sales and auctions that have raised billions for national economies.

Regulators have varied widely country by country, but I have always found the FCC and Ofcom very receptive to all forms of innovation in my professional capacity. In a chance meeting with Paul Jarvis (Ofcom Head Business Radio) at the RSGB Centenary Celebrations, I mentioned the ideas and proposition outlined above. This resulted in a very positive meeting with his team in London a few weeks later. This was his reaction, which he has kindly agreed to me quoting:

"The UK amateur licence is not modulation or use specific (apart from the commercial/broadcast restrictions etc). So there is no impediment from a regulatory perspective for experimentation throughout the amateur bands.

"Radio amateurs could develop/test spread spectrum techniques within existing amateur bands without specific Ofcom approval, although I would suggest it would be worth letting us know that the experiments are being conducted just in case we get a deluge of complaints!

"There are options for Special Research permits and Non operational test and development licences that we can issue if other (say commercial) bands need to be included.

"I don't think there is any impediment to encouraging amateurs to experiment and, like you, I would encourage considerate experimentation especially if it furthers the hobby and radio communications technology.

"My own view is that this is what the core of amateur radio is really all about – pushing the boundaries.

"I also think that if amateur radio could be credited for a breakthrough in technology it would do wonders in the credibility stakes"

Quoted from an e-mail exchange between Peter Cochrane and Paul Jarvis in August 2013 with the kind permission of Ofcom.

There we have it – the freedom to innovate and more – positive encouragement to do something different, to push the edge of the flight envelope, be and do differently and the chance to make contributions to the art and science of radio for the future.

QRV OR QRT? The last time I operated my own radio shack was 45 years ago, but I have kept an interest and maintained my licence. Sometimes I look at my list of hobbies and pastimes and reflect on amateur radio – will I ever go back and will I ever resume where I left off all those years ago? Sadly, I think not! After a lifetime of living and working at the leading edge of science, technology and engineering, I have decided that is always where I will want to be. So I have concluded that the only thing that would encourage me back is that addiction to change, challenge, dreaming and building that which most would consider impossible. The contents of this article spell out just one part of the opportunity space that might just do it for me!

But, how about you, and how about the wider community? I can hear the objectors and objections as I type these closing words. "Pah, where are we going to get signal sources for 60GHz and above even if we wanted to?" Well, look no further than the nearest car park and those £1 proximity sensors in the bumpers. There are many variants, but some make excellent 60GHz Wi-Fi transceivers. How do I know? Because I tried them over 18 years ago. And then, of course, there are those £40 microwave ovens at the supermarket giving a high power 1kW source at 2.4GHz, and they make great pumps…

The only limit here is our imagination and determination to explore, to learn, discover and contribute!

[2] www.inf.fu-berlin.de/lehre/WS01/19548-U/shannon.html