Microwave fixed links: bandwidth and spectral efficiency

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Abstract: Radio systems using higher-order modulation schemes can support a particular data-rate using less bandwidth than systems using lower-order modulation. However, engineers involved in frequency assignment for microwave fixed links are very familiar with the trade-offs: the higher-order schemes use less bandwidth but they require larger protection ratios and radiate at higher powers. Using wider bandwidth systems on selected links can deliver some startling results in relation to spectral efficiency.

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Frequency assignment

Microwave fixed links form essential infrastructure in the telecommunications networks. They are carefully planned and there are well-established frequency assignment and licensing procedures in place to ensure that they are not undermined by harmful interference.

The noise-limited frequency assignment method is a classical approach where single-entry and aggregate interference thresholds are maintained at levels below the receiver's noise level. An alternative is the interference limited method where the threshold for aggregate interference is above the noise; see [1] for a detailed explanation of both methods.

When a candidate fixed link is exposed to these frequency assignment procedures, the protection criteria must be satisfied at every receiver in the scenario. That is, interference from the candidate link's transmitters is calculated at all receivers operating in the same duplex sub-band within a defined range of the transmitter and *vice versa* (interference from established transmitters is calculated at the candidate link's receivers).

Normally, single-entry interference is modelled and compared with a threshold value. When the interference is equal to or less than the threshold, the assignment criterion is satisfied. The procedures can include two such tests for each pairing of a transmitter and a receiver; one modelling long-term interference and the second modelling short-term interference. Generally, the noise-limited and interference-limited descriptions refer to the long-term interference test.

The frequency assignment criteria is dependent on radio system characteristics. Figure 1 illustrates how the protection criterion for a receiver can be derived when there is knowledge of the receiver's sensitivity, modulation scheme and interference margin.

Here, R_{med} is the median received signal level, M is the fade margin, R_{ref} is the receiver's sensitivity and $C/(N+\Sigma I)$ is the *carrier-to-noise-plus-aggregate-interference* ratio required to support the radio's modulation scheme. M_I is the interference margin; that is, the degradation of noise due to aggregate interference. N is noise including allowances for the Noise Figure NF and fixed system losses L. The aggregate interference threshold is denoted by ΣI and the single-entry interference threshold by I. The protection criterion, or wanted-to-unwanted ratio, is denoted by W/U.

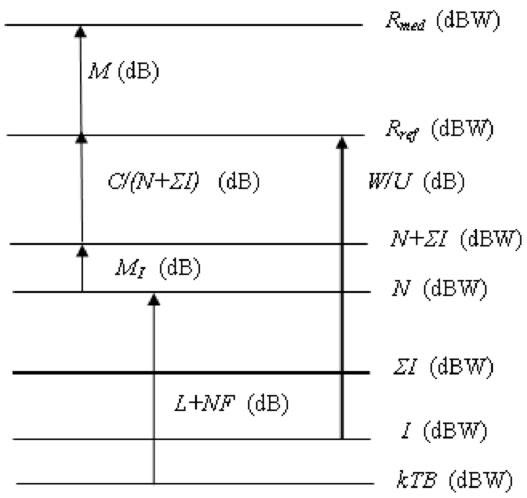

Figure 1 Noise-interference budget

I can be calculated assuming that a number of equal interferers contribute to ΣI. In Figure 1, W/U is the ratio of the fully faded wanted signal, represented by the receiver's sensitivity, to the single-entry interference threshold (test for long-term interference).

Inequalities

Whatever method is used to derive the W/U protection criterion, this ratio is highly dependent on the core $C/(N+\Sigma I)$ required to support the modulation scheme. Figure 1 also shows how a receiver's sensitivity level is dependent on $C/(N+\Sigma I)$.

In general, in any frequency band used by microwave fixed links, the spectrum manager will facilitate the deployment of various radio equipment types and the multi-raster channel plans specified for the Fixed Service. These options are desirable but give rise to enormous inequalities in the radio interference environment and between *requests* for frequency assignment. Figure 2 illustrates these inequalities: For some data-rate and some radio path, the narrower bandwidth (higher-order modulation) radio system radiates at higher power and is more sensitive to interference than the wider bandwidth (lower-order modulation) alternative.

Table 1 details these inequalities for a relatively small set of 38 GHz radio systems used in a recent study. Here we use the syntax *Mbit/s in MHz* to denote the radio system's data rate and bandwidth and values for R_{ref}, I and W/U are shown [2]. This is just a small sample of the radio systems available but even here we see ranges for R_{ref}, I and W/U of 16.5 dB, 13 dB and 13 dB respectively. This sample of, highly standardised, *classical* radio systems highlights the choices available to the radio link planner when considering a particular standard data rate. Here, for each data rate, there are two systems that satisfy the data rate exactly: One using a relatively higher-order modulation and one a relatively lower-order modulation in twice the bandwidth.

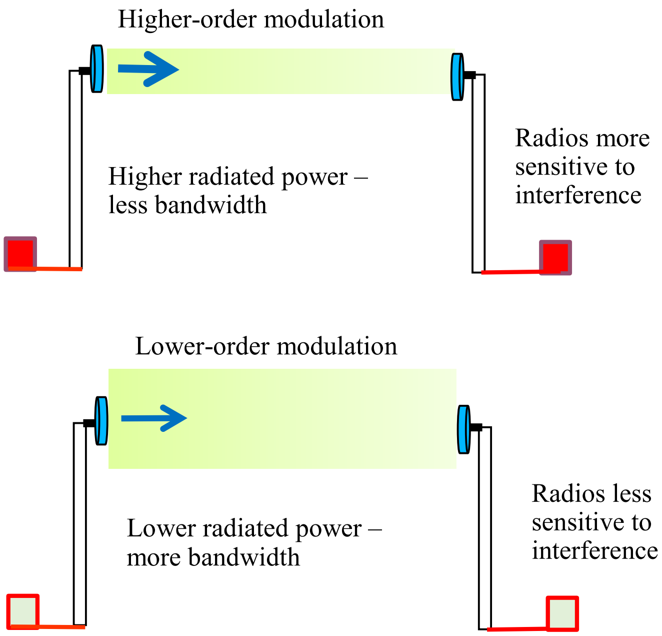

Figure 2 Inequalities

We can see while, for a particular data rate, the narrower bandwidth system has a higher *transmission efficiency* i.e. it sends more data per Hz, it is also the case that, idiosyncrasies aside, it has a higher R_{ref}, a lower I and a larger W/U.

In general, higher R_{ref} and larger W/U values mean that the relatively narrower bandwidth systems are more potent interferers (often R_{ref} is the start point for calculation of EIRP at the distant end of the link) and are significantly more sensitive to interference.

In professional practice, the assigner is often tasked with running a sequential frequency assignment service where new requests for frequencies arrive each day and are considered while taking careful account of existing deployments. Requests are handled one at a time and there is little opportunity for the assigner to consider spectral efficiency questions.

Typically, a *frequency exhaustive* technique is used where the assigner's software works through the ordered frequency list, assigning the first frequency where assignment criteria is satisfied. When followed strictly, this approach tends to pack the assignments towards one end of the frequency band and when the frequency list is ordered such that the first frequency is at the low end of the band, we see an effect known as *low end packing*.

Table 1 Radio Systems

Radio System (Mbit/s in MHz)	R_{ref} (dBW)	I (dBW)	W/U (dB)
8 in 3.5	-105.5	-138.4	33
8 in 7	-106.5	-132.9	26
2x8 in 7	-99.5	-132.4	33
2x8 in 14	-103.5	-129.9	26
34 in 14	-96.5	-129.4	33
34 in 28	-100.5	-126.9	26
51 in 14	-95.5	-129.0	33
51 in 28	-97.5	-130.4	33
155 in 28	-90	-128.9	39
155 in 56	-92.5	-125.4	33

Recent research

This low-end packing approach in professional practice lends itself to an analysis often used in the academic studies where the *minimum span* of frequencies required to resolve a set of requests is calculated; that is, the difference between the smallest and highest frequencies used by the assigner.

Some recent research [3, 4] has used this approach to investigate the use of wider bandwidth systems on selected links, measuring the impact on the total span of frequencies required for the request queue.

The study investigated fifty problems, each with fifty fixed links, with random geometry, packed into a relatively small area 0.25km x 0.25km with the aim of generating interference between requests (and so exercising the problem).

Each link was randomly assigned a data rate that can be resolved *exactly* by two of the systems shown in Table 1. Therefore, for each request, the assignment engineer has a choice between using a relatively narrow-bandwidth or relatively wide-bandwidth radio system.

The set of requests were first of all *tuned* co-channel, or near co-channel when operating on different rasters, and the *excess interference* (the amount by which the interference threshold is breeched) sourced from each transmitter and incident to each receiver was calculated.

Then the spectrum masks associated with each radio system's transmitter and receiver were used to calculate the *Net Filter Discrimination (NFD)* available between each pair of radio systems at discrete frequency offsets.

Using ideas from *graph theory*, each request can be represented by a *vertex* and the interference between requests by *edges*.

Using the results of the NFD calculations and the appropriate CEPT channel plan, these edges can be labelled with the minimum frequency separation required to resolve excess interference between each pair of requests.

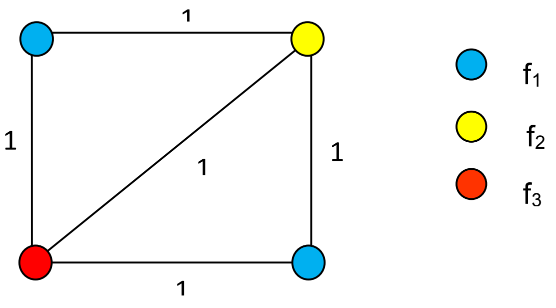

Figure 3 Example graph

With knowledge of the frequency separations required between each pair of requests in the problem, a frequency assignment for the entire request queue can be processed.

Figure 3 illustrates this *graph theoretic* approach: Here the four vertices represent four requests for frequency assignment and the edges linking these vertices are labelled with the smallest acceptable frequency separation (in this example 1 discrete frequency). The colours of the vertices represent the frequency assignments that satisfy these constraints.

With this study, we wished to investigate the idea of doubling the bandwidth used on some links and the impact that this has on the overall span of frequencies used. Initial investigations used mathematical programing techniques and a solver (software) to find exact solutions. The request queue was first of all resolved using the narrower bandwidth and then the wider bandwidth, with interesting results. Even though the bandwidth of each individual link was doubled when the wider bandwidth options were selected, the total amount of spectrum used was typically less than double that used by the narrower bandwidth systems. We then used the solver to run an *equipment selection* algorithm that selects the most spectrally efficient option for each request. Figure 4 shows these early results.

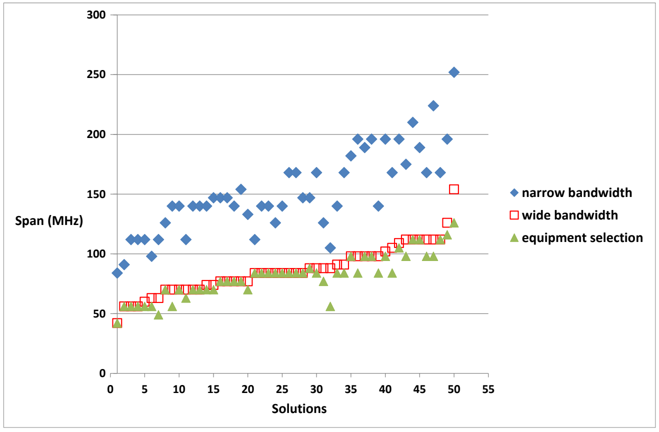

Figure 4 Frequency spans

Here, the average ratio of spans delivered by narrower bandwidth systems to wider bandwidth systems is just 1.77.

The equipment selection algorithm reduces the span of frequencies required to resolve the request queue by narrow bandwidth systems for 46% of problems. Spans are reduced by an average of 10.7% (over the 46% of problems where the algorithm is effective in reducing span).

These reductions in span far exceeded our initial expectations. An important point here is that, even where the algorithm is not effective in reducing span, we are able to double the bandwidth on a subset of links without any increase in span.

Later, some heuristic methods were developed. These heuristic algorithms work by summing the constraints on all edges incident to a vertex (request). Narrow and wide bandwidth options are tested and if the sum of constraints reduces by some predetermined criterion when the wider bandwidth system is tested then the algorithm selects the wider bandwidth system. The results obtained from the heuristics are equally encouraging.

Of course, these problems are a little abstract but nevertheless they have allowed us to test out some, really quite practical, ideas. The results show clearly that careful use of wider bandwidth systems is spectrally efficient.

Implications

These research efforts have kept focus on the problems experienced by assigners in the real-world and next steps could include studies that will consider the development of algorithms and professional software tools.

The fixed link assigner in the real world is often highly constrained and may not have the opportunity to consider more than one request at a time when running frequency assignment procedures. However, some further research effort could deliver viable algorithms for this environment.

The span of a frequency assignment is a useful measure in the studies but other measures such as frequency reuse, or *packing*, are perhaps more useful in the real world where we often see the entire frequency band utilised. The equipment selection algorithms could be useful to the spectrum manager wishing to obtain some practical measure of spectral efficiency.

Alternatively, the algorithms could be used to support frequency planning efforts or re-tuning campaigns.

Assignment difficulty (requests are rejected because they fail to satisfy frequency assignment criteria) can be very high in some frequency bands, often in specific areas. Methods, such as those discussed here that explore the solution space could have a radical impact.

Spectrum pricing often includes consideration of bandwidth but frequency assignment engineers have always understood the trade-offs between bandwidth, modulation, radiated power and protection ratios. A reasonable pricing regime would probably take account of the much higher radiated power levels and larger protection ratios required by the higher-order modulation radio systems.

Conclusions

A relatively higher-order modulation radio system can send a specific data-rate in half the bandwidth required by a lower-order modulation alternative. However, these narrower bandwidth systems will require a higher EIRP and a larger protection ratio in the radio interference environment.

For frequency assignment engineers in particular and spectrum managers in general, characterising the spectral efficiency of radios by their transmission efficiency and their impact in the radio interference environment by their bandwidth is not appropriate. The potency and sensitivity of radio systems are key.

The results outlined here are quite startling in some respects. They show that careful selection of wider bandwidth systems can reduce interference to the extent that either there is no impact on the span of frequencies utilised or there is actually a reduction in span. Further work could deliver tools for the professional environment that exploit the trade-offs discussed here and deliver tangible efficiencies.

References

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Biographies

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