"AM, FM AND ALL THAT!"

A NOTE ON MODULATION/DEMODULATION SYSTEMS WITH A FEW THOUGHTS ON POSSIBLE DEVELOPMENTS OF REQUIREMENTS AND TECHNIQUES.

By: N Morley CEng, FIEE, FIERE

Introduction

This is a paper for laymen - that is, laymen in radio engineering matters - and particularly for operational members of the Police and Fire Services who have communications interests and responsibilities. It is to such officers, many of whom must be constantly bewildered by conflicting statements on the subjects of this paper, emanating from apparently authoritative sources, that the subsequent discussion is addressed. It is not the intention here to argue cases for or against particular radio systems, but rather to present a few facts and explanations which, it is hoped, will help readers to a better understanding of the current situation; and to follow these with a brief consideration of possible future trends and work being done on new types of systems.

A simple question

Many of us are often asked to "answer a simple question", which turns out to be something on the following lines: "If you had complete freedom of choice now would you choose AM or FM?" As a simple question it ranks with the equally simple query; "Have you stopped beating your wife"? To neither question is there a simple answer - some explanation is needed. Just as a mathematical equation is worthless without precise definition of its terms, so is any simple generalisation on the subject of AM versus FM. To understand why this is so requires some appreciation of the technical factors involved and a knowledge of the historical background to the subject, and these will be provided in the next few paragraphs. (Laymen readers should not be alarmed at this prospect. The promise that this paper would be for them will be kept and technicalities will be minimal).

Fundamentals

In the radio field, modulation is the name given to the process by which radio waves are made to carry information. The simplest system of all is that in which the presence or absence of the wave is used to carry intelligence, like switching on and off a lamp to send coded signals. To transmit speech something a little more complex is needed and AM and FM are the two systems most commonly used at present for this purpose. The abbreviations denote Amplitude and Frequency Modulation respectively.

Amplitude Modulation (AM)

In this system speech is transmitted by causing it to vary the amplitude of the radio wave. The extent of the amplitude variation depends upon the level of the speech input (ie loudness), and the amplitude swings above and below its unmodulated value at the speech frequency. A simple example will illustrate the principle. Suppose we have a radio transmitter which with no input to the microphone produces an aerial current of 1 amp. When speech is applied to the microphone this aerial current may vary between the limits of 0.5 and 1.5 amps. As the variation in amplitude is half the unmodulated figure this condition would be called 50% modulation. Speech is a very complex collection of frequencies but if we suppose that a single pure tone at 1,000 cycles per second were applied to the microphone the amplitude would oscillate between the upper and lower limits 1,000 times per second. A louder sound input might cause the amplitude to swing between 0.4 and 1.6 amps, which would be 60% modulation. During this process the radio frequency remains constant.

Frequency Modulation (FM)

In this system the amplitude of the radio wave remains constant and speech is transmitted by causing it to vary the transmitter frequency. In this case the speech input level (or loudness) determines the extent of the frequency variation, and the instantaneous frequency swings above and below its unmodulated value, at the speech frequency. Again we will take a simple example. As amplitude remains constant throughout we will not specify a value for it, but we must instead stipulate the frequency. Suppose we take a nominal frequency of 100 MegaHertz, abbreviation 100 MHz. (A MegaHertz is what used to be called a magacycle per second and equals one million cycles per second, or Hertz.) That will be the precise frequency of the output when the transmitter is switched on but there is no speech input. When speech is applied to the microphone the frequency varies by a small amount, and it may swing, for example, between 100.01 MHz and 99.99 MHz, ie between 100 + 0.01 MHz and 100 - 0.01 MHz. The extent of the variation in frequency is called the Frequency Deviation, which in this instance would be 0.01 MHz or 10 kiloHertz (10 kHz). If we again suppose that a pure tone at 1,000 cycles per second (1,000 Hz) were applied to the microphone, the instantaneous frequency of the radio wave would swing between 100.01 MHz and 99.99 MHz 1,000 times per second. As stated earlier, the amplitude of the radio wave remains constant throughout this process.

So much for the fundamentals of the two systems. Readers will appreciate that only the simplest treatment has been given; also that the cases have been idealised. In practical systems the total elimination of one form of modulation from the other type of system may pose problems, but that comes under the heading of equipment quality, which will be mentioned later. Another system of speech modulation which readers may see or hear mentioned in connection with mobile radio systems is Phase Modulation (PM). This is very closely related to Frequency Modulation (FM), and for the purpose of this elementary treatment the two systems may be considered similar. (Sometimes the expression "Angle Modulation" is used to embrace both systems).

Historical

The first broadcasting and radio-telephony services employed AM exclusively. The FM system was developed in the United States in the thirties and was introduced into broadcasting services in some countries before the Second World War. In the United Kingdom, however, it was not until the post-war years, and the introduction of the VHF service, that FM was used for broadcasting. It is still used for the VHF broadcasting service, the transmissions in all other wavebands remaining as AM. The first FM mobile radio systems were actually introduced during the war.

Many readers will remember the introduction of VHF broadcasting in this country in 1950/51 and some will remember that for about a year the programmes were simultaneously broadcast by both AM and FM transmitters. Following this protracted trial the decision was taken that the service should continue as FM only. The BBC had, in fact, started tests to determine the relative merits of AM and FM shortly after the end of the war but, to quote from a professional journal of 1951, "Carried out on comparatively low powers, these tests did not prove conclusive, so a long term programme was therefore put in hand and a permanent high-power VHF transmitting station was constructed". That station was Wrotham, which is still operating, with an effective radiated power of 120 kW.

Characteristics of FM

When the first practical FM systems were devised in the early and middle thirties, because better performance could be obtained than from AM systems of similar transmitter power, some workers thought that something had been obtained for nothing, namely improved performance at no extra cost. As usual in such cases, however, this theory or hope proved false when the system was analysed mathematically and it was shown that the improved performance was obtained in exchange for increased bandwidth, ie a wider radio frequency channel was required for the transmission. Subsequent work on information theory has determined relationships between signal power, noise, bandwidth and channel information capacity, and has shown that, other things being equal, system performance is directly related to bandwidth. When bandwidth is unimportant, or at least is not a primary constraint, there is no doubt that for many purposes FM offers considerable advantage over AM, particularly in the improved rejection of noise and interfering transmissions. Unfortunately, in mobile radio generally this condition is seldom met, and it is never met in private mobile radio in this country. Before going further, therefore, we must consider this question of bandwidth a little more deeply, as it is vital to the whole subject.

Bandwidth

We have seen earlier that in amplitude modulation the transmitter frequency remains constant; but mathematical and experimental analysis of the process show that the act of modulation produces additional frequencies on each side of the fundamental frequency. In our previous example a modulating tone of 1,000 Hz was assumed. If the fundamental frequency was a 100 MHz, additional frequencies would be produced at 100 MHz + 1,000 Hz, and 100 MHz - 1,000 Hz, ie 100.001 MHz and 99.999 MHz. The total radiation in such circumstances would thus comprise three frequency components; 99.999 MHz, 100 MHz, 100.001MHz The spread of frequencies is seen to be 0.002 MHz or 2000 Hz, ie twice the frequency of the modulating tone. This spread is called the "bandwidth" and in an AM system the bandwidth requirement is always twice the highest frequency to be transmitted.

In an FM system, as we saw earlier, the frequency of the transmitter is varied and the extent of the variation is called the "deviation". Clearly if the radiated frequency is constantly varying about a nominal value the radio channel must contain the full frequency excursions and the minimum bandwidth required will be twice the system deviation. In this case, however, the requirement is not directly related to the modulating frequencies. Obviously in practice some limit has to be placed upon frequency deviation, and this is specified as "Maximum frequency deviation". Transmitters normally contain circuitry designed to prevent the maximum frequency deviation from being exceeded.

A mathematical analysis of FM is complex but it shows that the process of modulation, even by a single tone, produces a whole series of additional frequencies theoretically stretching to infinity either side of the nominal frequency. However, with "wideband FM", ie FM systems in which the maximum deviation considerably exceeds the highest modulating frequency, a bandwidth of twice the maximum deviation will contain the significant terms. Thus for wideband FM the bandwidth requirement may be taken as twice the maximum frequency deviation.

For wideband FM the bandwidth requirement is therefore considerably greater than that of AM, for the same modulation frequencies. It can only be reduced by reducing the frequency deviation. Unfortunately the major advantages of FM are related to this factor and reduction of bandwidth reduces them correspondingly. When the maximum frequency deviation is of similar value to the highest modulating frequency the system is called "narrow-band FM", and it is this type of system we are concerned with in private mobile radio. The minimum bandwidth of such a system is nominally taken as twice the sum of deviation plus highest modulation frequency. We will now consider the actual conditions obtaining in this country in the private mobile radio field, vis-à-vis conditions in other countries and in the broadcasting field.

A few facts and figures

We discussed in an earlier paragraph the tests carried out by the BBC to determine the best system for the VHF broadcasting service. They spend several years on these tests, culminating in the high-power, duplicated transmissions so the service was planned for an audio frequency spectrum up to 15,000 Hz, or 15 kHz. Thus the highest modulating frequency was 15 kHz, and it follows that the bandwidth required for this high quality transmission using AM was 2 x 15 kHz or 30 kHz. For FM the same audio frequency band was used but the maximum frequency deviation was 75 kHz. Thus the minimum radio frequency bandwidth required was 2 x 75 kHz or 150 kHz, and in fact a channel width of 200 kHz was assigned for the FM service. In the circumstances it is hardly surprising that FM was finally chosen, a greater cause of surprise being that the decision took so long.

Almost a comparable situation existed in the private mobile radio field when VHF services were introduced after the war. In this country channel spacing was initially 100 kHz in the high-VHF band (156-174 MHz) and only on the introduction of the low-VHF band in 1957 was the channelling reduced to 50 kHz.

For good commercial quality speech an audio frequency limit of 3 kHz is quite liberal so it will be seen that a mobile radio frequency channel of 40 kHz, allowing a maximum frequency deviation of 15 kHz, in fact provided a similar grade of FM performance to the broadcasting service described. In both cases the ratio of Maximum Deviation /Highest Modulating Frequency is five, and it is largely upon this factor, known as the Modulation Index, that FM system performance depends.

The circumstances described above are those which obtained at the time when many authorities decided to standardise on FM systems, and for unsophisticated radio schemes the benefit obtained by way of improved performance, particularly in respect of noise and interference, outweighed the somewhat more difficult maintenance involved.

FM was not generally adopted in this country for a number of reasons, one of them being the type of radio scheme in use by the Police and Fire Services. This was the spaced-carrier, multiple transmitter system, which provided an operational facility enjoyed by no other police service, viz simultaneous radio cover over the whole of a force area. The spaced-carrier system was not viable on FM, and there was no satisfactory FM system to replace it. Taking this operational requirement with various other factors into account the overall decision was taken to continue with AM.

In 1959 the channelling for private mobile radio was reduced to 25 kHz. This necessitated a reduction in maximum frequency deviation from 15 kHz to 5 kHz the new figure meaning a reduction in Modulation Index to less than 2. The performances of FM systems were seriously degraded by this change. In 1967 the channelling for private mobile radio was again halved, to 12.5 kHz, with a maximum permissible deviation of 2.5 kHz. With a maximum speech frequency also of 2.5 kHz, the Modulation Index becomes unity and FM systems operating in 12.5 kHz channels definitely come into the "narrow-band" category. The point to be made here is that the type of FM mobile system permissible in this country today can hardly be compared with the type of system available at the time when many authorities, especially in overseas countries, opted for FM. Incidentally, apart from one minor frequency band in New Zealand, in no other country today is the mandatory channel spacing less than 20 kHz.

"So long as it's black"

Most readers will have heard the famous choice offered by Henry Ford in connection with the immortal "Model T"; "You can have any colour you want so long as it's black". In a 12.5 kHz channel assignment, which must be the basis of any comparison of systems in the UK today, the real choice is almost as restricted. With each reduction of channel width the special qualities of FM have shrunk until, with the Modulation Index down to unity, differences between FM and AM system performances have become minimal. Mathematical analyses of the AM and narrow-band FM systems confirm that they are very similar indeed. It is strangely paradoxical that as the system differences have decreased the AM/FM arguments have tended to increase. This may be not unassociated with commercial influences, which we will consider later.

An analogy

The situation which has been reached regarding AM/FM might be likened to a comparison between two modern cars of similar price and with similar facilities and performances. The cars will probably perform similar functions and meet operational requirements equally well. Nevertheless, each may have minor features which appeal to some customers, or suit particular needs better. In any case each make will have its devotees prepared to swear by their choice.

Discussion and a few facts

It is true to say that any impartial authority will agree that differences between the two systems, judged on a 12.5 kHz basis, are marginal; and that the aspects of equipment design and manufacturing quality, and subsequent field maintenance are far more important. Points made in favour of FM are that there are still some benefits to be gained in "threshold" and "capture" aspects. The former relates to minimum signal working levels and the latter to the effect whereby a stronger signal over-rides a weaker one. Theoretically this is so, but it is important to keep in mind the environment in which mobile radio systems operate. Seldom do they operate in "steady-state" conditions. Due to obstructions, reflections, multi-path effects etc the normal case is that the mobile receiver input is continuously and often wildly fluctuating over fairly wide limits, and in such circumstances the practical improvement resulting from minor theoretical advantages is generally negligible. On the other hand it seems to be a fact that with 12.5 kHz equipments AM has somewhat the better performance in respect of impulsive interference, particularly when both equipments are at less than absolute peak performance, ie they have been in the field for a time. Again, however, with well designed and maintained equipments the difference is small.

It is relevant here to mention briefly tests carried out and decisions taken by various other authorities, and the first item comprises tests carried out by the AA in conjunction with the Post Office three or four years ago. Briefly, quite extensive tests were carried out in the London area, using comparable representative AM and FM equipments. The results were inconclusive as they did not give a clear indication of either system having an overall advantage.

At the beginning of this paper reference was made to the "simple question" postulating a complete freedom of choice. During the last few years one large association of mobile users found itself in that unusual position. This was the Joint Radio Committee of the Nationalised Power Industries. Prior to that time each section of the individual industries operated its own radio schemes using a wide diversity of equipments, in different frequency bands etc. Two or three years ago the industries decided to co-ordinate their planning, systems equipments etc, by means of the Joint Radio Committee. A new frequency band was negotiated for all services to move into as equipments were replaced. Because a change of frequency band was involved it was not possible to operate old and new equipments on a common frequency, and the Committee therefore had a complete freedom of choice of system. It chose to use AM. (The total number of mobiles operated by the members of that committee is about equal to the number in use in Police and Fire Services in England and Wales).

Coming right up to date, during the last month or two a major European country has elected to use AM for a national radio paging system which is being launched. This is unusual insofar as all other mobile radio services there are on FM. On the other hand there has recently been a decision to recommend FM for some ambulance services, mainly on grounds other than system performance.

The foregoing examples have been given simply to underline the fact that there is very little to choose between the two systems on a 12.5 kHz basis. Competent authorities have chosen both, in some cases for reasons unconnected with basic system performance. Nobody, therefore, should feel that a scheme using either system would be better if it used the other. Good equipment and maintenance are far more important factors.

In connection with equipment design and maintenance mention should be made of an increasingly serious problem which may not be generally appreciated. The general problems caused by the rapid growth of radio services and the rising levels of all forms of electrical interference are serious, but they are also obvious and are squarely faced by receiver designers. The problem which is not so obvious is often even more serious, and is that caused by the proliferation of high-power broadcasting stations. Few areas of the country do not receive very powerful signals from at least three VHF Sound transmitters two VHF TV transmitters and three UHF TV transmitters. To give some idea of the order of magnitude involved a quick check of figures given in the BBC Year Book shows that in England alone, the effective radiated power from the main transmitters on a single UHF TV channel totals the almost incredible figure of 13,000 kilowatts! When you multiply that by the number of channels, and add all the filler stations, local broadcasting stations etc, the total amount of "electromagnetic pollution" from this source is staggering. The argument as to its justification must be conducted elsewhere, but what it means in the mobile radio context is that receivers are often required to operate on low-level wanted signals whilst being subjected to enormous and continuous interference fields created by these broadcasting transmitters. This type of interference poses major problems in mobile receiver design and adds further weight to the opinion that minor idealistic considerations are irrelevant to the practical situation.

A little earlier the matter of commercial influence was mentioned. This should not be over-magnified but it is well to remember the fact that most overseas countries use FM exclusively, as they still have available relatively wide frequency channels. This being the case, radio manufacturers of those countries have concentrated exclusively on the design, development and production of FM equipment. To expect an impartial view from such firms on AM/FM is like asking the Gas Board for their recommendations on central heating!

One final point which should be mentioned in this section is that of area cover using simultaneous multi-station transmissions. On 12.5 kHz there is at present no proven scheme available on either system. Work is being done in several areas on this problem, some of which will be touched upon in the remainder of the paper.

Crystal-Gazing

We have been talking a lot about frequencies but let us look for a moment into the other type of crystal and try to predict something of what the future holds in the areas we have been considering. We have already seen how, in this country since the fifties, mobile radio channel spacing has been progressively reduced from 100 kHz to 50 to 25 and lastly to its present figure of 12.5 kHz. Is yet another reduction in channel spacing feasible?. Well, it is clearly possible in theory. Quite good speech can be contained in an audio band of 2.5 kHz. Using ordinary AM, therefore, with ideal equipment such speech would need only 2 x 2.5 kHz, ie 5 kHz, for its transmission.

In practical systems, of course, allowance has to be made for frequency drifts in transmitter and receiver, tuning drifts, etc. Even so, it has been claimed by one company that they have proved with protracted field trials a system working on 12.5 kHz channelling in the 450-470 MHz band. Supposing this claim to be substantiated, as frequency and tuning stabilities are almost directly proportional to frequency it will be seen that the system concerned has already exceeded the sort of stability standards necessary to allow, say, 6 kHz channelling at VHF. From stability aspects, therefore, the proposition of narrower channelling at VHF is, at least, a possibility. There are other factors involved, of filter design etc, which pose considerable problems, but it is doubtful that any is of such severity as to preclude the postulated reduction.

Alternatively, other systems may be considered, with smaller frequency requirements, such as Single Sideband. This type of system is in widespread use and giving great satisfaction in many services in the HF band, ie at frequencies up to 30 MHz. Harking back to an earlier section of the paper readers will recall that Amplitude Modulation of a transmitter by a single tone frequency produced two additional frequencies, above and below the unmodulated transmitter frequency. These additional frequencies are called "sidebands" because with speech transmission there actually are "bands" of frequencies. "Single Sideband" is a system in which, as the name implies, only one of these sidebands is transmitted. Somewhat more complex equipment is involved but the intelligence can be conveyed equally well in this way with the great advantage that only half the bandwidth is required, compared with the ordinary, double sideband case. Main problems with SSB are again frequency stability and filter design, but it is quite reasonable to assume that practical systems at VHF are not far off.

Turning for a moment to the question of frequency demands, it can very quickly be seen that the pressure on mobile radio frequency bands will keep increasing. The growth rate of mobile radio in this country is at present about 15%, at which rate the number in use will double within 5 years. It is considered unlikely that any constraint will be placed upon the issue of private mobile radio licences during that period. It is even less likely that the enormous frequency allocations devoted to broadcasting and military purposes will be squeezed to provide additional spectrum for mobile services. What is predictable, however, is that any technological advances will be eagerly seized upon as a means of providing a welcome easement of frequency planning problems. The possibility, at least, must be faced that at some future date there could be mandatory imposition of even narrower channel spacing.

Forward Planning

Some time ago the Directorate put a number of major projects in hand which were aimed both at devising means of improving current systems and at meeting future needs. Two of these projects are particularly relevant to the subjects we have been discussing, as they are both concerned with modulation systems and radio frequencies.

The first project comprises work being done for us at Swansea University on modulation systems. Briefly this includes a complete study and comparison of all types of modulation, including FM, AM, Single Sideband (SSB), Double Sideband Suppressed Carrier (DSBSC), and Double Sideband Diminished Carrier (DSBDC). The work has included studies on what are known as "synchronous" or "coherent" receiving systems and this area shows considerable promise for practical schemes of the future, and perhaps for shorter term improvements. Field tests have confirmed a host of laboratory findings and wider scale tests are planned.

It is not possible to go into the work in any detail here but it is worth metioning that a synchronous receiving locks on to a transmission and automatically stays precisley tuned to it. The action is similar to that of a mains operated electric clock which faithfully follows variations in mains frequency. (The clock in fact uses a synchronous motor). As it is relatively easy to stabilise the frequency of a base transmitter within very close limits, a mobile receiver tuned to it will acquire the same stability. The frequency of the mobile transmitter can then be derived from the stable receiver and the result is a channel which does not require the quite large allowances normally necessary to contain mobile frequency drifts.

The DSBDC system is looking promising with regard to simultaneous transmissions. The fact that the "Carrier" frequency (the middle frequency in our simple AM example earlier) is greatly reduced in amplitude leads to greatly reduced "beats" between transmitters, and this aspect is being investigated as a possible short-term benefit. (The reduction in transmitted power also helps in the general pollution problem).

The other major project involves another method of improving radio frequency utilisation, namely by using data transmission instead of speech for some purposes. In any operational sphere in which a large proportion of the radio traffic consists of routine messages which can be simply coded, channel time can be saved by sending such traffic by data transmission methods. One data channel can carry as much information as a large number of speech channels. Alternatively simple data transmission of a limited amount of information could be made over the ordinary channel. A major study and experiment has been launched to look into both operational and engineering aspects, and this is being discussed more fully in another paper.

Conclusion

An attempt has been made to provide simple explanations of the fundamentals of AM and FM, and related bandwidth considerations. The present situation in mobile radio has been discussed; also the frequency planning aspects which played a major part in its development. The proposition has been made that in the British mobile radio context AM versus FM is no longer a major issue; standards of design, manufacture and maintenance being of far greater importance. A brief account has been given of current work which is looking into possible systems of the future.

It is hoped some readers will consider the objective set in the opening paragraph to have been achieved, in which event the author will be well satisfied.

Mr Morley received his basic technical training with the RAF at Cranwell. He served in France and South East Asia. He joined the Atomic Weapons Establishment in 1949 and moved to HQ Signals Command RAF in 1955 working on ground/air communications, control towers and airfield navigational aids. He joined the Home Office in 1964 and is presently Deputy Director (Forward Planning).