FM, Land-Mobile Radio and the Amateur Radio Service
– a brief history

by Adam Farson VA7OJ/AB4OJ

Introduction

In this article, a brief overview of the underlying theory will show why FM is superior to amplitude-modulated emissions in the land and maritime mobile radio services above 30 MHz. A brief history of the evolution of these services, in civilian and military spheres, will follow. The impact of these developments on the Amateur Radio Service will also be discussed.

In keeping with the author's experience, developments in the United States will receive the most coverage, although European contributions (especially in the military arena) will also be discussed in some detail.

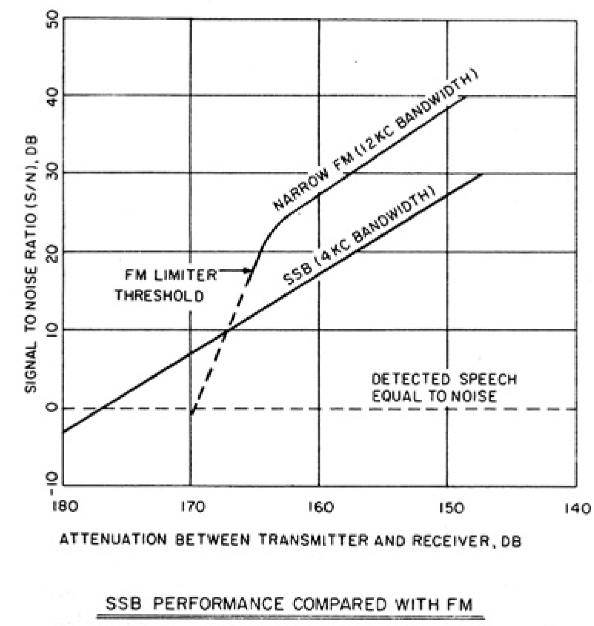
First, a bit of theory

A quick comparison of FM with SSB is interesting. Let us consider how path performance degrades with increasing path loss for each emission type. The curves in Fig.1 are illustrative:

It will be seen that SSB has a linear relationship between path loss and S/N (as does AM); there is no threshold "knee" as such. Modern DSP-based, heuristic noise-reduction (NR) techniques can often extract a usable baseband when the SSB signal is "down in the noise" (S/N < 3 dB). This has certainly been my experience with modern DSP-based HF transceivers, for example.

With FM, when the threshold is reached with increasing path loss, the S/N will degrade much more rapidly than for the SSB case, but intelligible voice audio is recoverable 3 to 6 dB below threshold - as long as incidental AM due to man-made noise is not too severe. Threshold-extension techniques (e.g. using a PLL demodulator with a loop filter cutting off at $\mathbf{f_m}$) can push the threshold back along the path-loss axis as much as 7 dB.

Fig.1: Simplified S/N vs. path loss curves for FM & SSB.



Important definitions:

FM modulation index $\mathbf{m = \Delta f / f_m}$ where **Δf** = peak deviation and $\mathbf{f_m}$ = highest modulating frequency.

Carson's rule: $\mathbf{TBW \sim 2 * (\Delta f + f_m)}$ where TBW = transmitted occupied bandwidth.

A characteristic of FM is that as **m** increases, the S/N above threshold will be higher for a given path loss, but the threshold "knee" moves to the right with increasing **m**. For **m** = 1 (typical in VHF or UHF FM systems with **Δf =** ±2.5 kHz and $\mathbf{f_m}$ = 2.5 kHz), the Carson's-rule occupied bandwidth is 2 (2.5 + 2.5) = 10 kHz. Compare this to 2.5 kHz occupied bandwidth for a typical SSB signal, which will be intelligible at path loss values well below the FM threshold.

Note that when path loss is sufficiently low to fully saturate the FM receiver's limiter (**full quieting**), S/N will be higher than for the same path loss value in the SSB case. (In the example shown in Fig. 1, this occurs at 150 to 160 dB path loss.) The reason for this is that AM noise which would be fully suppressed in the FM receiver will still appear in the SSB receiver's base-band output. Thus, if we can engineer our FM system for at least 10 dB of fade margin (headroom), overall path performance will exceed that of a comparable SSB (or AM) system.

Another advantage of FM is the **capture effect.** If two incident co-channel signals differ in amplitude by 6 dB or more, the FM receiver will capture the stronger signal and suppress the weaker. This confers greater immunity from accidental or intentional co-channel interference. Yet another factor favoring FM (as compared to AM) is that for a given transmitter output the primary power input is significantly less, as the high-level modulator stage is eliminated. This has obvious implications in mobile and portable radio designs.

These considerations drove the adoption of FM in land-mobile radio (LMR) as well as short-haul maritime R/T communications. Nowadays, virtually all short-range and inshore maritime radio communications are FM, in the 156-162 MHz range.

During the 1930s, mobile two-way radio communications systems came into use as technology made possible the design of transmitters which could be operated in vehicles. The advent of frequency modulation (FM) provided much clearer and less noisy transmissions, free from vehicular static. Almost all mobile systems operated below 40 MHz, since little was known about propagation at frequencies above that range, particularly in urban environments. However, research on the propagation of higher frequencies continued almost continuously from that time on.

The first significant FM LMR system was the Connecticut State Police low-band radio communications network, using sets designed and built by Daniel Noble and Fred M. Link. Soon, Noble joined Galvin Corporation (later Motorola). Galvin launched its own line of FM public-safety radio sets in approximately 1941.

The early successes of FM in US public-safety, local-government and commercial radio services led directly to the widespread deployment of 27 - 55 MHz FM tactical radio equipment in the US Army Signal Corps. To speed the adoption of FM, Edwin Armstrong freely licensed his FM patents to the US Government. By late 1943 to mid-1944, mobile and portable US-built FM sets, manufactured by Galvin, Link, RCA and others, were available to the US Army Signal Corps. Examples were the SCR-610 mobile and BC-1000 manpack. Transmitter power levels ranged from 0.5W or so for manpacks to 15W for mobiles. World War II demonstrated the superiority of FM transmission, which proved easier to use and more difficult to jam than the VHF AM systems in use by the Axis forces. Only U.S. forces used significant numbers of FM tactical ground radio systems.

Following WW II, many ex-servicemen returned to "civvy street" with a knowledge of radio technology and an appreciation of the value and convenience of mobile radio communications. Former military radiomen found ready and lucrative employment as maintenance technicians and installers serving the rapid growth of these new radio systems. Training courses for the coveted FCC Radiotelephone Operator's Licence (then required by law for LMR radio maintainers) sprang up in many cities, and were funded by veterans' education programs.

The late 1940s were equally important years for other aspects of mobile radio. AT&T introduced the first commercial public land mobile radio-telephone system in St. Louis in 1946. However, service was limited by a lack of channels, and the system was cumbersome to use, with half-duplex "push-to-talk" and manual connections via telephone-company "Mobile" operators. Nonetheless, 25 U.S. cities had public mobile telephone service by year's end. This system was termed MTS (Mobile Telephone Service).

As the demand for mobile telephony increased, the FCC assigned additional channels; IMTS (Improved MTS) supplanted MTS. IMTS featured up to 12 channels with automatic idle-channel selection, full-duplex working and direct subscriber dialing from the mobile as well as the fixed side. Analogue FM cellular service began to displace IMTS in the early 1980's.

Some surplus military radio equipment entered civilian life as low-band taxi dispatch radios, especially in New York and other cities. One should note, though, that ever more stringent FCC equipment certification requirements locked military surplus (except for military variants of previously-certified civilian radios) completely out of the LMR market by the early 1950's.

Development of specialized vacuum tubes with useful gain at VHF (some based on German designs), and the need to operate above the highest range of enemy intercept receivers, drove the development of 100 - 156 MHz AM air-to-air and ground-to-air radio.

Why AM rather than FM? Unlike FM, AM has no capture effect. This is vital in air-traffic control; if two aircraft are co-channel, the controller will be able to hear both. For this reason, 108-137 MHz (VHF) and 225 - 400 MHz (military UHF) use AM, not FM, to this day.

It should be noted here that during the war, several US law-enforcement agencies took advantage of the new high-band VHF technology by installing 118 MHz FM systems including mobile radios, and mountaintop links. After the war, the FCC allocated 30-50, 150-174 and 450-470 MHz (later expanded to 512 MHz) to LMR services, and reassigned the 118 MHz band to the aeronautical radio service.

Influence of LMR technology on the Amateur Radio Service (ARS)

Prior to, and immediately after WW II, all VHF R/T in the ARS was AM. For reasons which I have never fully understood, the immense advantages of FM over AM for local VHF/UHF radiotelephone communications were barely, if ever realized in the ARS until a US regulatory change in 1963 stood the whole thing on its head. The shift from AM to NBFM in the VHF bands started in the US. In 1963, the FCC mandated an occupied-bandwidth change in the LMR bands (30- 50, 150.8 - 174 and 450 - 470 MHz) from 36 kHz to 16 kHz. Channel spacings of 60 kHz (VHF) and 50 kHz (UHF) were halved; peak deviation was reduced from 15 to 5 kHz. Some existing sets could be "narrow-banded" by fitting narrower IF filters and turning down the deviation, but most were not economically modifiable. These sets were replaced with newer, narrow-band models, and the old sets found their way onto the surplus market. In no time at all, of course, enterprising hams had snapped them up and converted them to 2m and 70cm. A smaller number found their way onto 6m, which was never as popular due to TVI issues with VHF Channel 2 (54 - 60 MHz).

When the FCC authorized amateur repeaters shortly thereafter, amateur FM operation really took off as the popular mode par excellence, and all but eclipsed AM. Hams built repeaters out of mobiles, and also converted retired commercial base stations. As the number of amateur FM operators proliferated - especially in California and on the US Eastern Seaboard - the ARS also switched to 5 kHz peak deviation, where it remains to this day.

Innovative amateur groups built up extensive repeater networks, with multiple receiver sites and voters for optimum handheld coverage. Other groups, especially in the western states, engineered "intertie" networks linking repeaters and remote-controlled base stations via UHF-FM point-to-point links. Telephone-line interconnects, enabling a repeater user to place a call from his radio set to the public telephone network, were also provided where allowed (or at least tolerated) by telephone-company policy. These systems undoubtedly saved many lives. Most of this network deployment was accomplished using retired LMR equipment.

As the supply of surplus dried up, ham-equipment manufacturers started offering 6m, 2m and 70cm mobiles and handhelds, along with a few base-type radios. These were the progenitors of the modern, feature-laden dual- or multi-band FM mobile or handheld so popular among today's hams. Due to cost considerations, these wide-range multi-band sets do not have the front-end protection inherent to an LMR transceiver, and are thus subject to IMD and cross-modulation in high-RF areas. Thus, a demanding amateur will often prefer a "retired" LMR radio.

There is no doubt whatsoever that the huge increase in traffic on the 2m and 70cm amateur bands brought about by FM and repeaters has materially strengthened the argument for amateur retention of these bands. It is regrettable, though, that radio amateurs did not more exhaustively explore the benefits of threshold-extension demodulators for weak-signal FM working.

One of the most significant milestones was the release of surplus battery-operated portable FM equipment, especially handhelds, into the ham market. This equipment was hitherto unaffordable by hams.

Handhelds such as the famous Motorola HT-220 were the most reliable pieces of gear a ham could own; they also ushered in the era of personal portable communications in the ARS. The handheld/repeater combination revolutionized amateur emergency communications, putting them almost on a par with public-safety radio systems. In fact, many countries have integrated their national amateur radio societies into their emergency-planning operations, and for the first time ever (at WRC 2003) the ITU formally defined a disaster-communications role for the Amateur Radio Service.

Developments in Europe

Prior to WW II, the German and Dutch radio industries had discovered the virtues of line-of-sight propagation for urban mobile radio communications. This drove the deployment of VHF R/T systems in the 30 - 55 MHz band, and later (after WW II) in the 66 - 88 MHz band. The following statement from a pre-war German planning document is astounding: "Equipping *Panzer* troops with VHF radio enabled individual units to be tied into the command network. The control over fast-moving combat forces gave the *Wehrmacht* operational advantages." It has been said that tactical VHF radio was the "central nervous system" of the *Blitzkrieg,* as it facilitated the integrated command and control of infantry, armor and close air support. The German mobile VHF transmitters had 10 to 15W output; portables such as the *"Kleinfunksprecher D"* had 0.25 to 0.5W output, in the 30 - 55 MHz range.

Interestingly, two German airborne VHF radio sets – the FuG 15 (38 - 47 MHz) and the FuG 18 (24 -75 MHz) supported both AM and FM. These sets were developed in 1943-44. The FuG18 was a transceiver in the modern sense, with a common master oscillator and an up-converting transmitter. The reason for the inclusion of FM is unclear, but this mode may have been intended for use in *Funkspiel* (radio deception) operations against the RAF Ascension FM agent radio system[1], and perhaps even against US Army tactical VHF-FM nets after D-Day. *(In this connection, it is noteworthy that one of Edwin Armstrong's engineers absconded to Germany in 1941 with a full set of his employer's FM notes. He was never caught.)*

Manufacturers such as Siemens, Telefunken and Philips (Valvo in Germany) responded to this need with the surprisingly rapid development of suitable tubes. Some captured German VHF sets found their way to the US; Bell Labs received several of the excellent VHF tubes used in these sets. These designs gave rise to the famous "acorn" tube (e.g. 955) and frame-grid UHF tubes.

German successes with VHF tactical mobile radio in WW II fed directly into the deployment of such things as the 66 - 88 MHz FM LMR networks in post-war Germany. Examples are the national *Autobahnpolizei* network, and radio systems operated by urban public-transport agencies. In a manner paralleling developments in the US, European public and private entities adopted VHF FM land-mobile communications in the 66–88, 146-174 and 440-470 MHz bands starting in the 1950's. Manufacturers such as Pye (part of Philips after 1965), Storno, STC, Marconi and Motorola were the main equipment suppliers. As had occurred earlier in the US, the shift from 25 to 12.5 kHz channel spacing in the 1970's released significant quantities of LMR gear into the amateur community.

Military tactical VHF radio in the UK

In the British Army, the use of the VHF band (27-55 MHz) for tactical field radio was proposed during WW II, but there was considerable opposition to its use. This diffidence arose from entrenched use of ground-wave in the low HF range, uncertainties about VHF path performance in wooded or hilly country, and the requirement for sky-wave transmission on medium/long-haul circuits. The sky-wave requirement dominated the Army's radio-equipment policy until spectrum congestion, and severe night interference in the Far East, forced a re-examination of the problem.

Doubtless, a factor which accelerated the move to VHF was the considerable success attained first by German, and later by US Army forces in their use of the VHF band for infantry and armored formations, as well as for infantry/armor intercommunication. One should note that the British Army's gradual adoption of VHF came quite late in the war, and that they had German and US experience to build upon. It was nevertheless a bold venture, which ultimately succeeded. Even so, the British Army relied mainly on HF ground-wave, using low-powered sets in the 2 – 9 MHz range, right up to war's end. It did not fully commit to VHF FM until it standardized the WS88 FM manpack and the "Larkspur" radio family after WW II.

Recent trends

Ever-increasing pressure on available spectrum drove attempts to squeeze more channels into the available space, and also brought about major spectrum reallocations – mostly at the expense of the UHF TV bands, which were much less utilized than spectrum managers had anticipated when they were first assigned. In a few cases, under-used amateur spectrum was also reallocated – notably the 220-222 and 420-430 MHz ranges in Region 2. FM channel spacings were progressively reduced, first to 12.5 kHz, then to 6.25 kHz. At this narrow spacing, modulation index $\mathbf{m} < 1$; thus the S/N advantage of FM over AM is almost lost.
An alternative modulation method, ACSB (amplitude-compandored SSB) was proposed and tested in field trials in the 1990's, but proved to be so susceptible to AM noise and interference that the user community ultimately rejected it in favour of FM.

Various digital modulation systems have begun to take hold, especially in public-safety radio networks. In police and other local-government radio services, digital modulation methods are easily encrypted and can thus be made very secure. The major disadvantage of any digital modulation scheme is that the bit-error rate (BER) goes to infinity at the threshold; this causes loss of synchronization between the receiver and transmitter, destroying the link. To ensure acceptable fade margins, these systems must be engineered with a larger number of base stations and repeaters, and higher ERP.

So we finally come back to the "old standby", FM. It will still "get through" in a wide variety of topographical situations and equipment configurations, with relatively inexpensive equipment that is also easy to maintain and repair.

Acknowledgements

- *The author wishes to thank Brian Austin G0GSF for his invaluable assistance and constructive comments in researching and preparing this article.*
- *Source for Figure 1: "A First Primer describing SSB", TMC, 1960.*

[1] G. Pidgeon, "The Secret Wireless War", p. 100. UPSO 2003. Ascension may have been the only British use of FM during WW II.