Section 28

VEHICULAR COMMUNICATIONS

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The History of Land-Mobile Radio Communications*

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Summary—**This paper on land-mobile radio communications was prepared for the noncommunications and nonmobile radio specialist. The early pioneering work of the police is covered, and after a brief statement about the early use of mobile transmitters, the Connecticut State Police two-way FM system is described. From the introduction of FM into the Connecticut system to the present, engineering efforts have been directed toward the improvement of selectivity, the elimination of spurious responses and spurious radiation of the equipment, and in general, toward technical improvements which would make possible both an increase in spectrum utilization and an increase in channel loading. In the more recent embodiments of equipments, transistors have been used for the power supply, for audio amplifiers, and for complete receiver circuit design. While the use of single-sideband modulation and the general characteristics of random-access systems are under investigation, advantages have not been disclosed which would justify a switch from FM to some other modulation system. The efficiency of frequency utilization must be increased, and any system which offers a substantial improvement over FM will be given careful attention.**

Land Vehicular Communications

THE EARLY history of land-mobile radio communications is a history of police pioneering. The police of the U. S. have always been identified with the innovators in the communications field. As early as 1877, the Albany, N. Y., Police Department installed five telephones in the Mayor's office, connected to the precinct police stations; this was only two years after Alexander Graham Bell developed the telephone. In 1880 the Chicago Police Department installed the first police call box on the street, and three years later the Detroit, Mich. Police Department installed one police telephone, at a time when there were only seven telephones in the entire city.

In the radio field, spark transmitters were used by the New York Harbor Police in 1916 to communicate with their boats and other boats in the harbor. The Pennsylvania State Police installed point-to-point radio telegraph between headquarters and posts on 250 kc, back in 1923.

Just for a bit of perspective, remember that in 1904 Indianapolis was the automobile manufacturing center of the world, with Stutz, Marmon, Cole, National, and Dusenberg in the area, and it was during this year that the Indianapolis Police replaced the horse-drawn paddy-wagons and automobiles. The police began to use their first motorcycles in 1909, and in 1917 the Detroit Police began using automobiles with two men per car parked at police telephone booths along the streets. They did not patrol, but stayed in the booth between calls. A telephone in each booth supplied communications; a potbellied stove in one room, the coal bin in another, took care of the winter temperatures.

To a man of vision, the need for direct communication with moving police automobiles was clear. That man of vision, who refused to accept repeated failures in his attempts to establish practical radio communications with moving police cars, was Commissioner William P. Rutledge, of the Detroit Police Department. In 1921, only four years after the city pioneered the use of automobiles for police work, Commissioner Rutledge purchased a Western Electric 1-A, 500-w broadcast transmitter and installed it in police headquarters. This was before the days of crystal control, and the

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unit was a self-excited oscillator-modulator combination with two WE-212D's as oscillators, and another pair for modulators, and with a 1500-v motor generator for the power supply. For a period of six years, Commissioner Rutledge and his organization tried to develop a practical system to provide satisfactory voice communications to the moving cars. Their point of failure was the receivers. They could not build receivers which would work reliably in the police cars. Both voice and radio telegraph were tried, but the basic problem of receiver instability and lack of sensitivity limited the coverage. With each new year they found new approaches, but all were failures. The accumulation of frustration became so strong that, in 1927, the station was shut down and the radio room was locked up. During the six-year period, they had also battled a merry-go-round of license changes. When the station was first opened on May 23, 1921, it operated under the amateur license W8BNE, working on 200 m. But on August 16 of the same year, the license was changed to experimental W8XAB and the wavelength changed to 375 m. In 1922 another change put it on a provisional limited commercial license KOP on 360 m, which was changed in 1923 to 286 m, again in 1924 to a Class-A broadcast station on 277.8 m, and back again in 1926 to a limited commercial license WCK on 144.8 m. Even then the peregrinations were not complete. Later in 1926 the station was moved back to 200 m with a Class-A broadcast license; it was changed again in 1927 to a limited commercial grant for Station WCK on 144.8 m. According to one of the rulings in 1922, the Detroit Station KOP was required to provide broadcast entertainment during regular hours, with the police calls interspersed as required. Finding suitable performers for the broadcast programs was difficult, and the police band was given a notable workout.

Although Commissioner Rutledge closed down the radio station in 1927, he did not give up. He was convinced that the modern automobile had given the criminal an advantage in speed that could not be overcome by the use of police cars controlled by telephone. The prohibition era of crime flourished in the nation, and big city bootleg gangs were in ruthless control; slayings and corruption paced a nationwide major increase in crimes of all types. With the automobile, the criminal could strike hard and speed away with little chance of interference from the police cars awaiting calls at the telephone police booths. Patrolling without communications was a futile exercise. Commissioner Rutledge was desperate when he closed the radio room in 1927, but he did not give up.

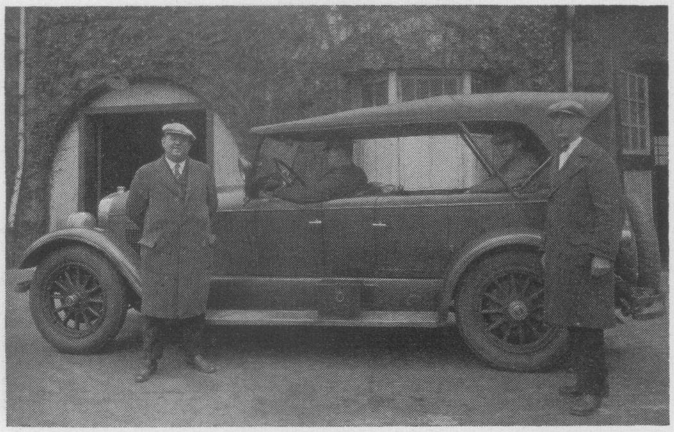
Remember that 1927 was still the early days of radio. Most home radios used B and C batteries for power and A batteries for storage, and even the car broadcast radio did not make its appearance until 1930. Short-wave radio was still 200 m, so Commissioner Rutledge was pressing the state of the art with his proposed police system on 144.8 m.

During the summer of 1927, Robert L. Batts, a young student from Purdue University, was working at a radio parts store in downtown Detroit. He developed quite a following of do-it-yourself customers who were purchasing kits to build radio sets. One of his customers was a young Detroit motorcycle policeman, named Kenneth Cox, and he and Bob Batts frequently discussed the possibility of making a radio receiver work in a police car. Batts had been using a superheterodyne receiver with a loop in a Dodge truck for tracking radio interference. To him the problem of car reception seemed simple. In the fall, when Batts went back to Purdue, he and Cox continued to communicate by mail, and Batts sent along suggestions and sketches for the construction of a police radio receiver. Late that fall, Cox went to Commissioner Rutledge and told him he could make a radio work in a police car. He had built a breadboard model thoroughly cushioned with foam rubber, and he deliberately dropped the receiver on the floor in Rutledge's office to show how rugged it was. It still worked. Cox received the assignment from Commissioner Rutledge to develop the receiver and he began a campaign immediately to entice Batts back to Detroit.

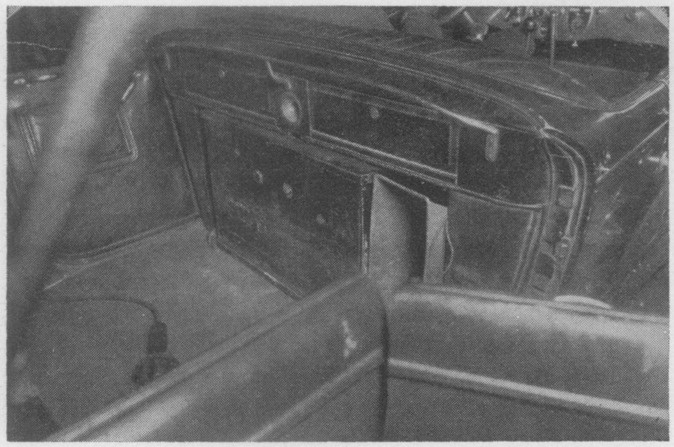
After some jousting with the Federal Radio Commission, a new construction permit was granted on February 4, 1928, to move the equipment to Belle Isle for operation on 144.8 m, and later on 94 m for the starting of new tests. Perhaps we should describe this 94-m assignment as the UHM of the early radio days.

Batts was finally prevailed upon to return to Detroit as a patrolman (that was the only way Commissioner Rutledge could pay him), to start work on the development of the new receivers. Bernard Fitzgerald and Walter Vogeler were given the job of rebuilding the Western Electric 1-A transmitter from a self-excited unit to a crystal-controlled MOPA, and Batts started on the new receiver design. The new receiver consisted of three stages of tuned RF, using the newly-available screen grid type-322, a 200-A detector, a 201-A first audio amplifier, and a 112-A output tube. Copper shielding compartments in the RF and detector sections, with locked-tuning capacitor adjustments, contributed to the electrical and mechanical stability. Heavy duty 135-volt B-batteries were used, and a 6-volt storage battery mounted on a running board provided the A-power. The A-battery drain was 1.1 amperes, and it was necessary to switch the storage batteries every four days.

Station W8FS first went on the air April 7, 1928, transmitting to a new receiver in cruiser No. 5 (Fig. 1)—and it worked! The receiver stayed tuned and reception was satisfactory all over the city. After nearly seven years of persistent effort, Commissioner Rutledge's dream had come true, and the improved communications system soon proved its value for the apprehension of criminals. The radio-equipped cruisers caught hold-up men, car thieves, and burglars, sometimes seconds after the call was reported to the dispatchers at police



(a)



(b)

Fig. 1—Detroit police Lincoln cruiser #5. The first successful mobile radio installation, April 7, 1928. (a) Car showing running board battery installation. (b) Receiver box and speaker back of the front seat.

headquarters. At times, the car was just around the corner or almost in front of the place from which the call originated. With this initial success to spur him on, Batts carried on an extensive program of field testing and built new and improved receivers to equip the entire fleet of police cars.

The pioneering of this early police radio system was truly the beginning of the land-mobile radio communications industry. The Detroit Police Radio System drew world-wide publicity, and visitors arrived from all over the world to inspect the system. Other city police departments planned radio systems, and like Detroit, they were forced to build their own receivers. In September, 1929, the Cleveland Police Department was the second system to go on the air with a few cars. Batts, who had moved on to Indianapolis in October, 1929, put that city police department on the air on December 24 of the same year.

There were other firsts. The pioneering record would not be complete without a brief mention of the first freight train installation. Arthur Batcheler, Supervisor of Radio for the Department of Commerce Radio Division, took part in a test demonstration April 23, 1928 on a New York Central freight train. A train consisting of a locomotive, 125 freight cars and 2 cabooses, was equipped with an experimental General Electric 50-watt radiotelephone installation to furnish communication between locomotive and caboose, or between either locomotive or caboose and the signal towers which the train passed en route. Batcheler reported, in a letter to the Department of Commerce, "The demonstration was a most successful one and communication was carried on continuously over the entire route." He also stated, "The Federal Radio Commission no doubt will have to provide channels for operation of this service, which, in the future, is destined to come into general use." For the freight train applications the problems of cost, installation, and maintenance outweighed urgency, and the work was dropped. For the police use of radiotelephone, urgency was the paramount consideration, and the number of installations increased rapidly.

The pioneering work of the Detroit City Police had broken through the barrier to successful radio communications to the police cars. Equivalent systems were established in many cities. The State Police became interested also, and on May 17, 1930, the Federal Radio Commission granted the State of Michigan the license for 5000 w on 1642-kc daytime and 1000 w at night. The Michigan State Police Station was on the air by October, 1930.

As soon as the use of broadcast transmission to police cars became routine, it became apparent that there was an urgent need for acknowledgment and talk-back. Lt. Vincent Doyle, the radio man for the Bayonne, N. J., Police Department, decided to do something about the two-way communications matter; in March, 1933, he was on the air with the first two-way police radio system, using REL AM equipment on 33.1 Mc. Four police cars were equipped. The units used superregenerative receivers and noncrystal-controlled MOPA transmitters with a pair of 210's in the final. The stations were operated on the temporary experimental license W2XCJ.

Bob Batts had not lost his pioneering spirit. In 1933 he had the Indianapolis Police Radio Division on the air with a 200-w base station and two 20-w mobile two-way units. The mobile transmitter units were high powered compared to the ones used in the initial installations in other parts of the country. Batts teamed his 20-w transmitters with 6-tube VHF AM superhets of good sensitivity, with 6-v tubes. The base station was equipped with a 100-foot antenna, and very reliable two-way communications were established despite the fact that quartz crystals were not available for either the transmitter or the receiver control. The lack of crystals and the high battery drain discouraged a further expansion of the system, even though the test results were excellent. The Indianapolis Police Department also pioneered the installation of superheterodyne receivers on police motorcycles. In 1931 there were thirty-two solo motorcycles in the Indianapolis Police Department equipped with AM superheterodyne receivers operating on 2442 kc, using P. R. Mallory vibrator power supplies. Although a few commercial receivers were available, the equipment used until 1935 in nearly all of the police radio systems was of the do-it-yourself variety—and excellent equipment it was, too, for the state of the art. Late in 1931 the Bosch Corporation offered the first commercial compact superheterodyne receiver with a separate dynamotor power supply, which eliminated the B batteries. The Sparton Company in Michigan offered receivers for a brief period. The introduction of the Mallory vibrator power supply in 1931 was an important step forward, with a resulting decrease in operating costs and an increase in reliability. RCA and GE entered the mobile radio field in 1936, with F. M. Link following, and Motorola began selling police radio receivers in 1937. As a result of hearings held in 1936, the Federal Communications Commission issued Order No. 19, dated October 13, 1937, which allocated twenty-nine VHF channels to police departments in the band 30.58 to 39.9 Mc. This order was a milestone in the development of two-way VHF police communications. The use of crystal control for both transmitters and receivers became universal, and in 1938 the FCC established the maximum allowable frequency tolerance of 0.05 per cent on frequencies above 30,000 kc.

Interest in two-way communications spread to the power companies, and in 1938 George Underhill established a system for the Central Hudson Gas and Electric Company of Poughkeepsie, N. Y. Earl Glatzel established the second system a few months later for Detroit Edison. In 1939 the FCC defined police communications as emergency service and recognized the power utilities with provisions for special emergency licenses. By then, a number of commercial brands of equipment were available, with RCA, F. M. Link, GE, and Motorola as the leaders.

Two-way VHF communications were standard for city installations, but state police were still operating on one-way broadcast systems. It remained for Colonel Edward J. Hickey, Commissioner of the Connecticut State Police, to establish the first two-way state police system in the country, and it was the privilege of the author of this paper to pioneer the system as the first police FM installation. The success of the Connecticut system started the nationwide switch from AM to FM.

The details of the Connecticut State Police FM radio system design may be found in the November and December, 1940, issues of *Electronics*. The shift from AM to FM was a radical step, but the use of FM, or more properly PM (phase modulation), in the Connecticut system only partially accounted for the success of the system. In nearly all city two-way AM installations, the base station transmitters and receivers were located at the most convenient spot, which was usually the City Hall or some other police-controlled facility. An ambient noise level at the base station receiver sometimes reached several microvolts, and only strong signals from the mobile transmitters could get through. For the Connecticut system, each tentative base station location was checked for noise level, and a test run was made with a mobile unit maintaining communications with a temporary base station installation. The optimum location was picked for both low noise level and high elevation, and telephone wire connections were provided to control the station from the barracks radio dispatch office.

It would be obvious to any engineer that the best place for the mobile antenna would be in the middle of the rooftop of the automobile, and so, to gain maximum communications range, this was the location selected. Tapered steel-tubing fishing rods were purchased and mounted on a spring held in place by a molded collar. Coaxial cable connected the antenna to the transmitter and receiver in the car trunk. This combination of the selection of low-noise and high-elevation base station locations, and the use of efficient mobile antenna installations assured the success of the system. While good coverage would probably have been achieved with AM, the unique capture effect of FM made it possible for ten individual police-troop base stations to operate simultaneously on the same frequency assignments without significant interference. Two frequencies were used, 39,400 kc for the base station transmitter and 39,180 kc for the mobile transmitters. The use of two frequencies was a unique approach, designed to make it unnecessary for the low-powered mobile transmitters to compete with the adjacent area 250-w base stations transmitting from high antennas. To provide car-to-car communications, provisions were made for switching extra crystals into the mobile transmitters for operation on the base station frequency. Since there was only a difference of 220 kc, the switch could be made without retuning the transmitter and with only a nominal loss of power. As a practical matter, it was found that the adjacent base stations could go on the air simultaneously, and each base station would capture its own mobile stations. Where there were exceptions to this rule in the case of a preferred transmission path existing between the mobile unit and the opposing station, it was only necessary for the mobile unit to move along slowly and stop on the peak of the standing wave to capture the desired station. In general, it may be said that each base station operated as an independent system; but that every base station was capable of communicating with every other base station, and of taking over communications with the patrol cars in an adjacent area when a base station failure occurred. This two-frequency, three-way design provided flexibility for state-wide communications with generous factors of safety and with a minimum of equipment complexity. An alternate system using individual frequencies for each area either would have eliminated interarea communications, making it impossible for a car to switch from one base station to another as it traveled across the state, or would have made it necessary to equip each car and base station with complex multichannel equipment.

The major virtue of the use of phase modulation in the Connecticut system was not the wideband FM noise-reducing characteristic which is usually identified with the FM broadcast service. The virtues of FM noise reduction are realized only when the signal exceeds the noise level, but in the mobile communications systems, the chief noise and the most serious noise limitation are produced by the radiating automobile ignition systems. The ignition-pulse interference nearly always exceeded the signal level and, at times, pulses would reach peak values several hundred times greater than the level of the desired signal. Each pulse would take over the limiter temporarily and, in effect, would gate the receiver for the duration of the pulse. This was an inherent brute-force pulse noise suppressor, and it outperformed the pulse noise gates sometimes used in AM receivers. In fairness, it should be stated that there existed one AM pulse noise suppressor system which followed the envelope of the received modulated wave and cut the pulse at the instantaneous amplitude of the associated wave. With this envelope-following pulse clipper, an AM receiver offered competition for FM in the one category of ignition noise suppression. There were, however, other important attributes of the FM system which combined to outclass the general performance of AM for mobile communications. It was often necessary to maintain communications with very weak signals. With the AM system, the moving car passing through the standing waves would produce a flutter of modulation as the signal dipped from a usable level to an unusable level. It seemed impracticable to design the AM receiver with time constants necessary to control the distortion caused by the rapid changes in the radio and the subsequent audio signal levels. With FM the audio volume was not a function of the signal level, and as a result the standing-wave modulation produced some noise flutter as the signal dipped below the reception level, but the standing-wave modulation would yield readable signals where communication was lost in an equivalent AM system. The sensitivity of an FM receiver could also be maintained at a very high level with generous factors of safety to compensate for tube aging and for circuit detuning. With a limiter functioning normally at $\frac{1}{4}$ v, it was possible to design a receiver which would amplify the front-end ambient noise to 15 or 20 v at the limiter. Tube aging and circuit detuning could reduce this limiter voltage substantially with no apparent effect upon the reception performance. Perhaps the final point of advantage of FM over AM was the superior squelch system. The AM squelch consisted of a simple gate which would be opened when the received signal was strong enough to trip the blocking voltage on the grid of the audio amplifier. Unfortunately, the receiver did not recognize the difference between noise energy and carrier energy, so that a strong noise would also open the squelch. The police officer in the car would understandably adjust the squelch so that the noise would not open it, and as a result the sensitivity of the receiver would become the rather low sensitivity of the squelch control. The FM equipment employed in the Connecticut State Police system was manufactured by the F. M. Link Company and was, in general, an adaptation of high-quality AM standard units but with the necessary change-over to FM to provide increased gain with an effective limiter and a frequency detector, but the squelch system used was the same as that employed in the AM equipment.

When the first Motorola FM mobile communications equipment was designed, a new squelch system was introduced, which became the standard of the FM industry. This circuit, which became known as the "differential squelch," balanced the voltage change produced by the characteristic FM noise reduction in the presence of a carrier, against the voltage resulting from the rectification of received noise. With this arrangement, the squelch would open with a very-low-level signal (0.15 μv) when there was little noise present, but as the noise increased, the signal level required to open the squelch also increased. The system was so balanced that the loudspeaker would always be activated at a signal-to-noise ratio so low that the voice was unreadable. With this squelch system, noise bursts would close, rather than open, the squelch gate, and the sensitivity of the receiver was no longer limited by the sensitivity of the squelch. A further receiver design refinement substantially increased the effective sensitivity of the receiver by decreasing the inherent first mixer noise. The final receiver design could provide excellent communications in low-noise areas with a signal input voltage of less than $\frac{1}{2}$ μv. A signal generator input to the receiver of 0.4 μv would produce a 20-db receiver noise reduction. The receiver squelch system, the high sensitivity, and the reserve gain were the keys to the extended range and the reliability of performance made possible when the equipment was used in systems with the base stations installed at high-elevation and low-noise-level locations.

The mobile transmitter designs were straightforward, with a crystal oscillator feeding a modulator, which, in turn, activated two quadruplers, a doubler, and a final amplifier. Perhaps it should be noted that, with the PM transmitter using the same power amplifier tube as that used for AM, the average power could be increased to a value approximating the peak power of the AM output, or to maximum tube rating. The 20- to 25-w AM transmitter became a 35–40 w FM transmitter, with an 807 tube in the final amplifier. Two tubes in the final amplifier and an increased power supply provided a 50- to 60-w output with no modulator change.

The first FM two-way mobile communications installations were characterized by exceptional reliability of communications and exceptional range of communications as compared to the usual AM installations.

In the early days of FM equipment design, the receiver selectivity was wide open, with an IF selectivity 50 kc wide, 6 db down, and 200 kc wide, 60 db down. The receiver's spurious and image responses were only 40 or 50 db down. The deviation of the transmitter was uncontrolled, with a modulation sensitivity varying all the way from 18 kc to 45 kc for the same signal input. The final test for modulation was a voice test with a microphone, and the deviation was not measured. The spurious radiation of the transmitters was practically uncontrolled, with substantial spurs radiating interference. These faults, however, were important only in a crowded spectrum and they did not limit or interfere with the performance of isolated systems. In 1940 there were only a few thousand transmitters on the air, and interference was not a major factor, but by 1948 the number had grown to 86,000 transmitters, with a leap to 695,000 in 1958, and the number projected for 1963 is 1,390,000 transmitters. The technical history of mobile communications equipment design since 1940 is a history of development to improve the efficiency of spectrum utilization.

While the police pioneered the development of the first practical mobile communications system, the engineers of the radio communications industry carried out a continuous program of refining the equipment design to increase the spectrum loading. As spectrum crowding developed, bringing with it the inevitable interference problem, the needed reduction of transmitter spurious radiation, the reduction of receiver spurious responses, and a substantial improvement in receiver selectivity followed rapidly. Additional refinements reduced the transmitter noise, introduced instantaneous deviation control, and provided receiver design to minimize desensitizing and intermodulation interference. Without going into laborious detail, a look at the specifications for modern "transistorized" units will partially define the progress which has been made.

General

Two-Way Mobile Radio Station: single case ($3\frac{1}{4}\times 13\frac{3}{8}\times 17\frac{1}{2}$ inches; 29 pounds).

Transmitter

Power Supply: Transistor oscillator type "dc transformer."

Power Output: RF 30 or 50 w, 40 Mc; 25 w, 160 Mc.

Transmitter Spurious: More than 85 db below carrier.

Frequency Stability: ± 0.0005 per cent of assigned frequency. $-30°$C to $+60°$C with $+25°$C reference.

Modulation: As specified, ± 5 or ± 15 kc for 100 per cent at 1000 cps.

Circuits and Multipliers: Phase modulator and deviation control; doubler; tripler; doubler-driver; power amplifier.

FM Noise: -50 db below ± 3.3-kc deviation at 1000 cps.

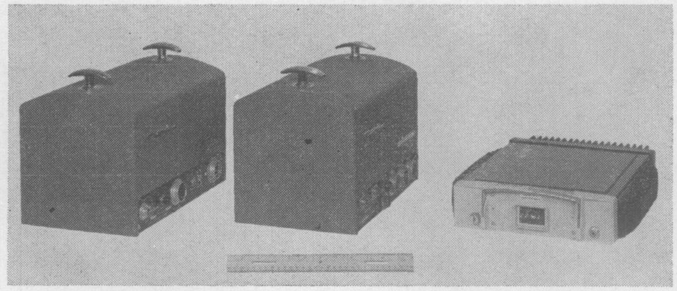


Fig. 2—1940 separate FM transmitter and receiver "breadloaf" packages compared to the 1961 single-packaged transmitter-receiver with transistor-type receiver.

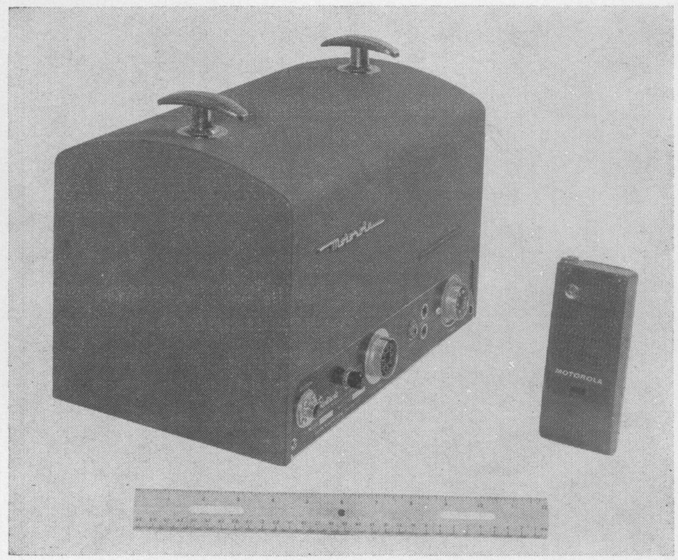


Fig. 3—1940 receiver compared with the equivalent 1961 transistor-type receiver, which is complete with speaker and battery supply.

Fig. 4—Quarter-wave cavity selector used for base station control of intermodulation and desensitizing in the 160-Mc band.

Receiver

Selectivity: -100 db at ± 15 or ± 32 kc, as specified.
Channel Spacing: Designed for original 40- or 60-kc spacing and, for split channels: 20, 30, 40, or 60 kc.
Sensitivity: Depends upon frequency, etc. 0.3 μv to 0.6 μv for 20-db quieting with 50 ohms of RF input impedance.
Stability: ± 0.0005 per cent of reference over temperature range -30 to $+60$°C.
Squelch: Noise compensated. Threshold sensitivity, 0.15 to 0.25 μv. Also tone-coded squelch available.
Audio Output: 5-w to 3-ohm load.

Of all the problems which have limited spectrum loading, desensitizing and intermodulation have been the two most difficult to control. The design of 455-kc IF selectivity providing 100-db protection at the edge of the channel was readily accomplished, but desensitizing and intermodulation are related to receiver front-end RF rather than IF selectivity. A mobile unit parked in the shadow of an opposing or undesired station may attempt to receive a 1-μv signal from its parent base station. Since the opposing station, which may be on a frequency several channels removed from the desired channel, can pass signals through the acceptance band of the RF section of the mobile receiver, this high signal level can blank out the desired 1-μv signal from the distant station even though the nearby station cannot be heard because of the tight IF selectivity. In a somewhat similar pattern, two nearby transmitters, radiating strong signals on, for example, the second and third channels removed from the referenced desired signal, can mix in the front end of the receiver to generate a mixing product directly on the frequency of the desired signal, and strong enough to wipe out the desired distant station signal. The only immediately apparent solution to such interference problems is RF selectivity comparable to that obtained in the IF section of the receiver, but of course, at 50, 100, and 450 Mc, this is completely beyond the art. By stressing the linearity of the RF amplifier circuit design and by resorting to multicircuit high-Q front-end filter stages, the engineers have provided a modest 65- to 70-db protection.

Particular cases of interbase-station interference problems were solved by the use of very-high-Q quarter-wave cavities. Obviously, such cavities were too large for mobile station use and even this radical approach failed to provide the 100- to 150-db adjacent-channel protection necessary for adequate spectrum loading. While the use of cavities in the receiver base station front-end design did not offer complete solutions, it did increase the efficiency of spectrum utilization and solved many specific problems which developed as new systems were added in crowded areas. Fortunately, the recent introduction of the varactor and its promised application to the up-converter and down-converter circuits offers a potential solution to both desensitizing and intermodulation, with the expectation that the needed 100- to 150-db protection may be achieved in the future.

Spectrum loading for maximum utilization is a three-dimensional problem involving frequency, space, and time. Frequency division has been the traditional approach to radio spectrum utilization. The available channels may be increased by narrowing each channel so that radio systems are operating with less frequency separation. The original FCC rule making established 40-kc bandwidths for the 25- to 50-Mc band, 60-kc bandwidths for the 148- to 162-Mc band, and 100-kc bandwidths for the 450- to 470-Mc region. Subsequent channel splitting changed these bandwidths to 20 kc, 30 kc, and 50 kc, respectively. With the development of intermodulation and desensitizing protection of 100 db, or greater, channel splitting to 15 kc for the 160-Mc band, and 25 kc for the 450-Mc band, may be expected to provide additional spectrum loading.

As the bandwidths are narrowed, the automobile ignition-pulse-noise interference in the lower bands becomes a limiting factor for systems range. The inherent pulse-noise suppression characteristics of FM receivers employing 40-kc and 60-kc bandwidths made the use of additional pulse-noise receiver gates unnecessary, but with the split channels, especially in the 25- to 50-Mc band, the range of communications is decreased by the ignition noise and the effectiveness of a system can be restored only by the use of a self-gating pulse-noise suppressor. These pulse suppression systems are beginning to be used in industry, and a typical application may be found in the Motorola low-band transistor receivers which utilize the following straightforward design: While the pulse is delayed by a line section in the front end of the receiver, a parallel circuit amplifies and shapes the pulse for use as a gating signal which temporarily blanks the receiver input at the instant of the arrival of the opposite-number delayed pulse. Since we are dealing with pulse durations of a few microseconds, the receiver gate may be closed for the duration of the pulse without destroying the intelligibility of the voice transmission. In actual tests, with weak signals and with strong high-repetition rate ignition-pulse noises completely destroying the intelligility of reception, the activation of the pulse-gating system reduced the noise to such a degree that voice intelligibility was restored. It may be said in general that the increase of spectrum loading by splitting channels to narrower bandwidths results in a degradation of the signal-to-noise ratios of the operating systems. The use of effective pulse-noise-gating circuitry becomes necessary to substantially restore both the range and the quality of reception.

While the development of the land-mobile communications systems has been almost wholly concerned with the use of FM or PM, tests have been carried out to explore the potential of both single-sideband and random-access systems for this service. There are two major disadvantages to the use of single-sideband in mobile applications:

1) The complete suppression of the carrier is not at present practicable because of the problem of generating restored carrier in the receiver within the tolerance requirements for low-speech distortion. The necessary maintenance of the locally generated carrier at ± 30 c at 150 Mc would demand design tolerances which, at the very least, are beyond the economic tolerance of the industry.
2) Single-sideband reception cannot tolerate ignition pulse-noise interference. The range and performance of ordinary single-sideband systems in comparison to ordinary FM systems is inferior to the point of unacceptability without the use of some form of single-sideband pulse-noise suppression.

Obviously, both objections may be limited by the extension of the art. The vestigial carrier can be transmitted with the sideband to synchronize the local receiver carrier generator. It is also possible to establish community carrier-frequency reference transmitters which would be used to provide the synchronizing frequency for the restoration of the carrier in all receiver systems operating in the area.

The ignition-noise problem is a temporary problem, since a normal development of the automobile may be expected to eliminate such noise-making transmitters; but in the meantime, it is feasible to equip single-sideband receivers with pulse-noise suppressors which will bring them into performance competition with FM receivers.

There seems to be no information about the equivalent of the flutter noise (standing-wave modulation effect) as applied to single-sideband systems.

One significant advantage of the use of single sideband transmission should be stressed. It should be obvious that, because of the reduced average power transmitted, potentially interfering intermodulation products will be greatly reduced.

So far, there has been no strong trend in the mobile industry to move toward single sideband, because the equipment is, in general, more costly, more critical in terms of adjustment and maintenance, and without substantial advantages within the present art for either improved performance or for increased channel loading. This is not the final word, however, and the pressure for radio spectrum space may eventually force the development of systems which may be operated without interference and with no more than 5-kc channel spacing. It should be noted in passing that the generation of many single-sideband channels properly coordinated can be accomplished at a given base station; but by the very nature of the mobile station, each car installation must be regarded as a separate and isolated system, thus limiting the use of such multiplexing to the fixed stations.

While the single-sideband approach to increased channel loading will be scrutinized constantly by the mobile radio industry, a second approach of interest is the wide-band time-sharing system sometimes referred to as the "random-access" system. At present, the application of the random-access discreet address system seems to have more potential interest for military communications than for use as a substitute for the FM police and industry communications systems. In the random-access approach, each transmitter sends short pulses which carry both the voice and the essential coding. Simultaneous conversations in the same spectrum band are possible because each transmitter has a relatively low-duty cycle transmitting the short pulses, and different transmitters share time on the same channel. Since the transmitters are not synchronized, there will be occasional coincidence of pulses. To minimize the resulting interference, the pulses from each transmitter are coded to particular receivers, so a receiver recognizes only the pulses addressed to it. The coding, or addressing, is accomplished by using redundant transmission, with each single transmitting pulse replaced by several pulses which carry the same modulation, but which are transmitted on several carrier frequencies and/or in different time slots. A receiver may have a fixed address, and a transmitter may have a variable code so that it can change the address to reach different receivers. The required bandwidth for a single RF channel is somewhere between 1 and 10 Mc, depending upon how many simultaneous talkers are to be accommodated in a given communication system. The maximum permissible number of simultaneous messages per Mc depends upon the selected modulating and addressing scheme, and on the geographical distribution of the stations. Several simultaneous messages per Mc may be possible. In a wide band-system, three or four hundred stations might find it possible to operate simultaneously, providing instant communication to associated addressee mobile units. The random-access approach substitutes time division for frequency slicing. Since we are now reaching frequency division limits which make it difficult to achieve improved efficiency through the use of further frequency slicing, the potential for increasing efficiency of spectrum utilization offered by other systems approaches must be thoroughly explored. It is too early to evaluate the competitive significance of random access and other similar time division systems for industrial and special mobile service applications, but the use of such systems would seem to be limited to special operational requirements of the type encountered in military operation.

In the frequency, time, and space dimensions of radio spectrum communications loading, there is the time factor which involves the time on the air for any transmitter as a factor independent of any modulation system used. The taxi radio dispatch service has succeeded in maintaining high-channel loading by operating systems which share time on the same channel. It is probable that the effectiveness of channel time-sharing could be greatly increased by the use of automatic selection and lock-out techniques to insure the protection of the station using the air. Either carrier control or wire line interconnections could be used, with proper monitoring by a computer memory and logic system to provide for an equitable distribution of time on the channel for the sharing systems.

The third dimensional factor, space, is concerned with a balance of many elements associated with the problem of geographical separation as a means for allowing channel assignment duplication without interference. It is obvious that elevation, antenna height, radiated power, tropospheric and ionospheric transmission, and FM capture-effect are all pertinent to the influence of space upon channel loading. Of the factors mentioned above, the FM capture effect has contributed the greatest positive force for permitting channel duplicate assignments with a reasonable geographical separation between systems. Unfortunately, the FM capture effect is reduced as the channel width is decreased; and while there is a gain in the total number of channels available for assignment, there is a loss in the number of duplicate installations for a given area because of the necessity for increasing the geographical spacing between systems operating on the same channel. Until adequate protection is provided against intermodulation and desensitizing, the splitting of channels may not add as many interference-free systems as might be possible with the wider bandwidth assignment in areas where modest geographical separations permit same-channel operation.

The single-sideband system does not provide a capture effect, but where the carrier is eliminated, the radiated energy follows the random surges of energy radiation which is characteristic of voice communications, and the average interfering power radiated is low. It would be expected that compared to the equivalent performance of a pair of FM systems, single-sideband systems operating on the same channels would cause less intelligibility-destroying interference. Every proposed new system of modulation displays both advantages and disadvantages. Until there is some *substantial* advantage in the use of the frequency, time, and space dimensions for one mobile radio modulation system over all others, there is very little incentive for changing the present FM pattern of systems design.

The change from AM to FM did not alter the physical characteristics of mobile equipment significantly. The transmitter was still a combination of frequency multipliers and a power amplifier, with the phase modulator substituted for the amplitude modulator. The receiver became a double-conversion superheterodyne with RF and IF amplification, but with the addition of limiters and a frequency detector which differentiated it from the AM unit. The first major construction change came with the adoption of the single-chassis construction for both transmitter and receiver, as opposed to the earlier approach where the transmitters and receivers were separate units. The single chassis reduced the size of the equipment, but perhaps the real advantage was the reduction in manufacturing costs.

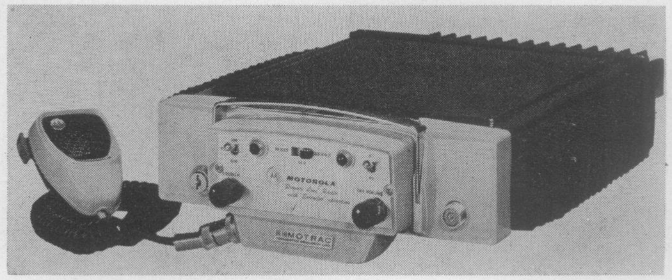


Fig. 5—The 1961 mobile FM station with transistorized receiver and power supply.

The most radical change in equipment construction came with the application of the transistors and solid-state diodes. The first application of transistors provided a power amplifier for the receiver output to increase the audio level. High audio level in police cars is particularly desirable because of the necessity for overriding the wind noise produced at the time of a high speed chase.

The second solid-state application was the use of transistors in a power supply oscillator circuit to step up the 6- and 12-v battery supplies to the high voltages required for receiver and transmitter operation. Both the transmitter power amplifiers and the transistor power supplies proved to be more reliable than the tube, vibrator, and motor generator equivalents. Size, weight, heat, and cost reduction were additional bonuses realized as a result of this application of solid-state devices. The present trend is toward the greater use of transistors in all mobile and portable equipment. There has been a complete change to transistors for both receivers and transmitters used in some portable applications. For the mobile units, the change-over has provided complete receivers with transistors and with no tubes, but the lack of high-power transistors for VHF amplification has limited the application to transmitter design. The use of transistors in the receiver has made additional reduction in the equipment, heat, size, and weight possible. Reports from the field, concerning the maintenance of new equipment built with transistors, show a substantial improvement in reliability over the record established with tube apparatus. The trend toward the utilization of transistors in equipment design will continue, and transistors will be applied to transmitter construction as soon as transistors with the needed high-power output characteristics become available.

The common carrier land-mobile radio service, pioneered by AT&T in 1946 with the St. Louis installation, has always used selective calling, which has also been available for use in the private systems. While the squelch provides protection against noise, it does not provide protection against unwanted carriers on the same frequency. Although selective calling would provide such protection, it also tends to slow down the operational response characteristics of the system, and for this reason, many systems owners have rejected selective calling. In operations where speed is less important, the use of selective calling has been discouraged by the substantial additional cost of the required accessory equipment. A compromise approach has been the use of selective squelch or tone-operated squelch. When the selective squelch system is used, the base station is equipped with a coded tone, usually operating at a subaudible level for the system, and the squelch systems in all of the associated mobile units will open only when activated by the base-station coded tone. The system requires that squelch code tones be allocated to avoid duplication in any given area. In the taxi service particularly, the use of coded squelch has been found to eliminate a high percentage of the unwanted and unrelated voice communications from other systems operating on the same channel. The coded squelch is a means for increasing the practicability of channel time-sharing.

While this paper has been primarily concerned with the pioneering work of the police and with the technological history of the land-mobile radio telephone systems development, the story would not be complete without some mention of the rule-making established by the Federal Radio Commission and, later, by the FCC, and of the qualification of new users and the growth of the land-mobile radio communication industry. The first rules in the format as we know them today (Part 10—Emergency Radio Service, and Part 11—Miscellaneous Radio Services) were adopted October 3, 1933, by the Federal Radio Commission. The FCC was established in 1934. The definitive standards for FM in the land-mobile services were not adopted by the FCC until it implemented the Atlantic City International Treaty of 1947, which was ratified by the U. S. on June 18, 1948. These technical standards were the same as those incorporated in our present-day rules up to the time of the split-channel rule-making proceedings of 1958. The 1948 rule-making established the land-mobile services on a fully licensed basis, extended the qualifications for licenses to many new users, and in general, established the foundation upon which the modern mobile communications industry has grown. From the original tentative allocation of frequencies for special emergency service, formal licensing has been extended to include, in addition to the public safety radio services, such services as land transportation, industrial radio, common carrier, and citizens band.

The continuing substantial expansion of land-mobile radio communications is inevitable. The EIA report on, "Private Land Mobile Systems in the United States," June 5, 1961, predicts that there will be 1,390,000 transmitters in service in 1963; 2,650,000 in 1968, and 5,000,000 in 1978. Both increased spectrum allocations and the use of new spectrum-stretching techniques must be adopted if growth is to be accommodated without an associated rise of interference to intolerable levels. Fortunately, the mobile radio engineers will have problems to keep them busy until 2012 A.D.

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