Escaping the Dead Zone: a Bottleneck in Humanitarian Ionospheric Radio Communications

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Abstract— **High Frequency (HF) radio communications are used in humanitarian work in areas where local networks are non-existent, or destroyed by natural disaster or human conflict. Direct point-to-point communications are realized over long distances, independent of local networks, using the ionosphere as a natural high-altitude reflector. HF ionospheric radio is essential for humanitarian organizations delivering basic healthcare in poor and remote areas. Normally, with proper frequency planning, ionospheric radio will easily connect all field teams in a contiguous area with a radius of 200-400 km. However, in recent years humanitarian organizations reported a "Dead Zone" that occurs at a short distance from the base, with good reception at larger distances. This local communication blackout causes a security hazard to the field crews. This paper investigates the phenomenon, and makes an inventory of its possible causes and drivers.**

Keywords— HF, ionosphere, Dead Zone, humanitarian, radio communication, antennas

I. Introduction

Before 1965, all intercontinental voice communications made use of commercial radio stations for High Frequency (HF, 3-30 MHz) radio links with distant countries. These facilities extended the landline telephone network with direct radio links, e.g., between Europe, New York, Buenos Aires, Cape Town, Tokyo, and Australia [1]. Those radio stations were quite advanced, and their commercial and social importance incited a lot of research into the nature of the ionosphere [2], antennas [3] and enhanced transmission and reception methods [4]. Several innovations used in modern wireless devices stem from that era. While transatlantic cables did exist at the time, they initially provided no competition, as their bandwidth was too limited to support voice transmission. This changed in 1956, when the first transatlantic cable with 36 telephony channels came into operation [5]. A bigger step was made in 1963, when the first geostationary communication satellite, Syncom-2, was launched [6]. Additionally, glass fibre submarine cables started to offer drastically widened bandwidths in 1988 [5]. This led to the demise of the large and powerful HF radio stations for telephony, as their income dwindled. Today, people from privileged countries are used to large bandwidths and high network availability, aspects that HF ionospheric radio communications cannot promise. As a result, mainstream interest in ionospheric radio has faded, and expert knowledge of the domain is dying out.

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Still, ionospheric radio has unique characteristics that are that are invaluable in the absence of local telecommunication networks and/or when low communication costs are essential. It is therefore still used extensively in Lower Income Countries. As the ionosphere is a natural resource, an ad-hoc communication lifeline is quickly realized. For distances up to 200-400 km, the launch angle of the radio waves is very steep [7] because of the important reflection height in the ionosphere, typically 250 km. It effortlessly covers the deep valleys between high mountains, and the field strength is more or less constant over that entire area. It is therefore selected for several niche applications:

- UNHCR has used it to maintain communications in difficult terrain and areas outside the reach of preinstalled Very High Frequency (VHF) repeaters [8].
- The Community Resilience in Central Africa program, of USAID, Invisible Children and Caritas, has installed HF radio systems to connect isolated communities in conflict zones to enhance security [9].
- Médecins sans Frontières, who provide basic healthcare in poor countries, use HF radio for their field work.
- Flying Medical Services in Tanzania fitted their airplane with HF radio equipment, to coordinate their work.
- In Antarctica, HF radio is used to collect climatological data from remote sensors [10] and transmit them to Spain via another HF radio link, over 12,700 km [11].

Especially the lower HF (3-12 MHz) frequency range is well suited for humanitarian communications, as a contiguous coverage area can be created around the coordination center, with a radius of 400 km or more. HF radio wave propagation is very efficient and it can be used without specialized knowledge, even though the underlying mechanisms are actually very complex [12]. Normally, with proper frequency planning, ionospheric radio communications will easily connect all field teams in the coverage area.

However, recently, Médecins sans Frontières reported a consistent "Dead Zone" - a zone in which reception is impossible – starting at a short distance from the base station,

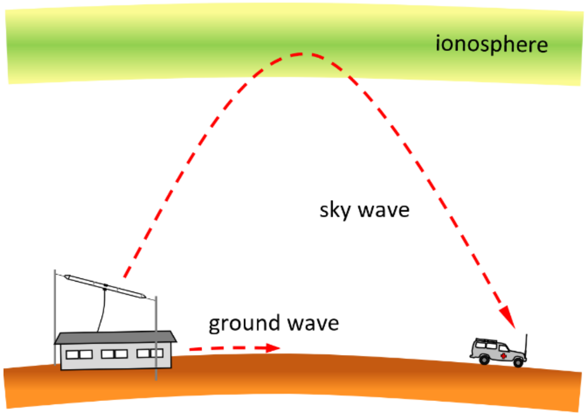

Fig. 1 Typical humanitarian radio link between a coordination center (hospital) and a mobile field crew (ambulance). The radio signal is transported by ground wave and skywave propagaation.

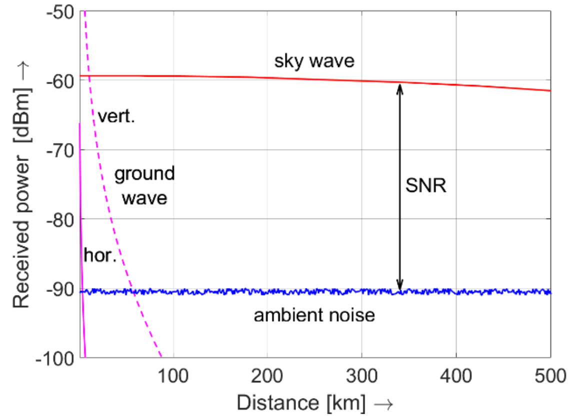

Fig. 2 Ground wave, skywave and radio noise for a 100-Watt transmitter, assuming and lossless isotropic antennas over average ground ($\sigma = 5$ mS/m, $\varepsilon_r = 13$). Frequency is 9 MHz, 14:00 LT, rural area in West-Africa.

while reception recovered at greater distances. This presents a security risk to the field crew working or transiting this zone. The problem occurred in the Central African Republic, Mali, Guinée Conakry, Mozambique and Afghanistan, and is not limited to a certain geographic location. The origin and drivers of this phenomenon are not very well understood. First analysis indicates that it may be caused by (a) ambient electromagnetic noise, (b) transmission above the critical frequency of the ionosphere, or (c) antenna characteristics. We will investigate them in this paper, assuming a typical humanitarian radio link, connecting a hospital to a field crew (ambulance), see Fig. 1. An arbitrary location in West Africa (10° N, 10° E) is used in this study.

In Section II the radio wave propagation mechanisms discussed, assuming lossless isotropic antennas. Section III describes the ambient electromagnetic noise. Section IV discusses frequency selection and the critical frequency of the ionosphere. Section V investigates the impact of the antenna characteristics. The paper concludes with a discussion and suggestions for further work.

II. Radio Wave Propagation

In this frequency range, for radio waves traveling from the base station to the mobile field teams, two independent propagation mechanisms can be distinguished: (a) ground wave, and (b) sky wave propagation, see Fig.1.

A. *Ground wave propagation*

At the lower HF (3-12 MHz) frequency range, at short distances from the transmit antenna, part of the signal will be received via ground wave propagation. Due to the finite conductivity of the soil, the electric field vector is tilted forward and the wave energy tends to concentrate close to the ground [13]. The waves seemingly "cling to the ground" and bend past the horizon. Ground wave propagation provides a very steady signal, but it has a limited reach and attenuation increases with increasing frequency. Vertical polarization is needed to excite the ground wave. As most humanitarian organizations use the horizontally polarized wideband antennas for their fixed installations, the amount of energy fed into the ground wave is limited. Fig. 2 shows the received power from a 100-W transmitter due to ground wave propagation over average soil, that has a conductivity $\sigma = 5$ mS/m and a permittivity $\varepsilon_r = 13$. The NTIA LF/MF propagation model is used [14] and lossless isotropic antennas are assumed. The continuous line represents the received power when the transmit antenna has horizontal polarization, the dashed line is for vertical polarization. The influence of properties of typical antennas will be discussed in Section V.

B. *Sky wave propagation*

Particularly at heights between 60 km and 450 km, the atmosphere is partly ionized due to short-wavelength radiation of the sun, generating free electrons [15]. The peak electron density in this plasma occurs between 200 and 300 km altitude ('F-region'), with a subpeak around 100 km ('E-region'). Radio waves entering the ionosphere interact with these free electrons and this causes refraction at or below this height [12]. The waves are being bent back to earth, as if a reflecting layer were present. The refraction in the ionosphere depends on the local electron density and is frequency dependent. Vertically emitted radio waves will only fully reflect if their frequency is smaller than the peak plasma frequency, or 'critical frequency' *fxF2* (or *fxI*) of the ionosphere. Therefore, to ensure contiguous coverage, the transmitter frequency must be below *fxF2* [16].

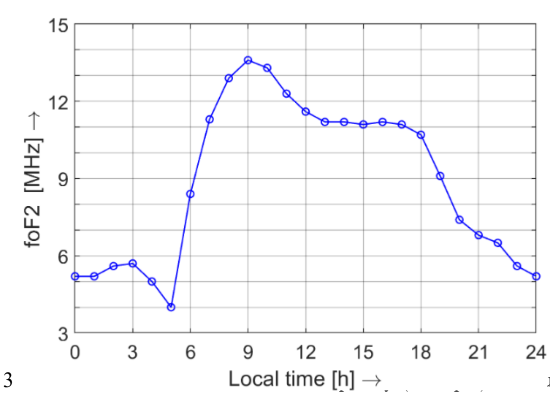

Fig. 3 [illegible] ured in June in Ilorin, Nigeria, during a solar cylce maximum. Figure adapted from [17].

As the electron density in the ionosphere depends on solar radiation, the critical frequency follows a diurnal pattern, which may vary from day to day. The structure and density of the ionosphere will also show seasonal effects and follow the 11-year solar activity cycle. Where *fxF2* could be as high as 10 MHz during daytime and 7 MHz at night during solar maximum, it may be as low as 6 MHz during daytime and 3 MHz at night during solar minimum. Fig. 3 shows the diurnal variation of the critical frequency in Ilorin, Nigeria [17], during a solar cycle maximum. Due to the important reflection height, the path length from transmitter to receiver is similar for the entire coverage area and the field strength does decay less than 3 dB with distance. Losses are lowest at frequencies close to, but below the critical frequency. Signal strength values, simulated using PropLab V3 [18] for lossless isotropic antennas are added in Fig. 2. These values are conservative; higher values are observed in practical set-ups. Normally, in the area were ground wave and sky wave produce similar field strengths, self-interference ('fading') will occur. Here, the use of a horizontally polarized transmit antenna has sufficiently attenuated the ground wave and there is no fading zone.

III. Ambient electromagnetic noise

In the frequency range between 3 and 12 MHz, the ambient electromagnetic noise ('radio noise') level is significant. It is caused by accumulated impulses of remote lightning flashes that are transported to the receiver via ionospheric reflection ('atmospheric noise') and unwanted emissions from electrical and electronic devices ('man-made noise') [19]. The internal noise of well-designed receivers is much lower than the ambient noise; consequently, the ambient noise is the limiting factor for the reception of weak signals [20]. Typical median *man-made noise* factors F_{am} are specified in Part 6 of ITU-R Recommendation P.372-14 [21]. Assuming the hospital is located in a rural area:

$$F_{am} = 67.2 + 27.7 * \log_{10}(f) \quad (1)$$

Where f is the frequency in MHz. At 9 MHz, F_{am} is 41 dB. Typical *atmospheric noise* factors are specified in Part 5 of P.372-14. They vary with geographical location, season and time-of-day. When we assume that the hospital is in an arbitrary location in West Africa (10° N, 10° E), in June and around 14:00 UTC, the atmospheric noise factors F_a can be calculated using the ITU-R-Noise software [21]. At 9 MHz F_a is 48 dB. The *combined noise* factor is 49 dB. The noise power Pn at the input of the receiver can be calculated using:

$$P_n = F_a + 10 * \log_{10}(B) + 10 * \log_{10}(k * T_0) \quad (2)$$

Where P_n is the noise power in dBW, B is the receiver bandwidth in Hz, and Bolzmann's constant k = 1.38 $*10^{-23}$ m^2 $kg/(s^2.K)$, and temperature T_0 = 300 K. For a typical bandwidth of 2.4 kHz, the predicted noise power is -91 dBm. This value, which determines the reception limit, has been added to Fig. 2. We can now see that – assuming isotropic antennas – the signal-to-noise ratio (SNR) is sufficient to establish and maintain the radio link. The ambient noise level increases when a lower transmit frequency is selected. At 3 MHz the rural man-made noise F_{am} is 54, the atmospheric noise is F_a is 64 dB, resulting in a combined noise factor of 65 dB and a noise level at the receiver input of -75 dBm. This is another reason to select a transmit frequency close to (but below) *foF2*. For completeness: the atmospheric noise values predicted by P.372 seem a little high, and normally the man-made noise levels in residential areas will exceed the atmospheric noise. On the other hand, these values will be exceeded during frequent lightning storms in the rainy season. No on-location noise measurements were made.

The predicted ambient noise is independent of the distance and by itself poses no problem for the sky wave reception. Of course, strong man-made noise from individual sources could cause significantly higher levels locally. However, there level would be highly dependent on proximity, and their effect local, over a few 100 meters at best. A moving vehicle would easily identify such a noise source, due to the increasing noise level at approach, and decreasing level when passing the source. To block reception in a zone of several kilometers in size, high noise power would be needed, as the coupling from source to victim would be ground wave propagation, see [19]. Therefore, unless we consider deliberate jamming in a war zone, it is unlikely that ambient noise is the cause of the reported Dead Zone.

IV. Transmission above the criticial frequency

As explained in Section II, vertically emitted radio waves will only reflect if their frequency is smaller than the critical frequency *fxF2*. Therefore, to ensure a contiguous coverage, the transmitter frequency must be below *fxF2* [16]. Radio waves with higher frequencies pierce the ionosphere when they hit the ionosphere vertically. When they hit the ionosphere at lower angles, they may still reflect up to a higher frequency f_{max}. The relationship between f_{max} and the zenith angle θ (or the elevation angle α) is approximated by Martyn's 'Secant Law' [22]:

$$f_{max} = fxF2\ \sec\theta \quad (3)$$

$$f_{max} = fxF2\ / \sin\alpha \quad (4)$$

At a transmit frequency f_{tx} above *f0F2*, the maximum elevation angle can be calculated:

$$\alpha_{max} = \sin^{-1}(fxF2/f_{tx}) \quad (5)$$

From which the minimum distance or 'skip distance' D_{min} can be calculated. According to McNamara [23], for short distances on a curved Earth, each elevation angle α in the polar graph can be related to a distance D using:

$$D = 2\,R\,\left[\cos^{-1}\left(\frac{\mathrm{R}\cos\alpha}{R+h'}\right) - \alpha\right] \quad (6)$$

Where R = 6378 km is the radius of the Earth at low latitudes, and h' is the virtual reflection height, here taken as 300 km. The results are represented graphically in Fig. 4. A transmit frequency that is a mere 1% higher than *fxF2* already results in a skip distance of 80 km. At smaller distances, the radio wave is no longer reflected and only a small fraction of the energy will arrive via a scattering mechanism [24], and the signal strength will be at least 45 dB weaker. At greater distances, good signal strength will be observed, as depicted in Fig. 5. Also, at very close range, where ground wave coverage is present, a radio link is possible.

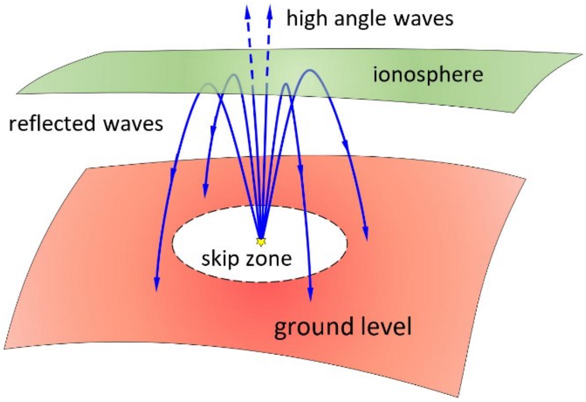

Fig. 5 Skip zone, occuring when the transmit frequency is a few percent higher than *fxF2*. The skip zone quickly becomes very large when the transmit frequency exceeds *fxF2*.

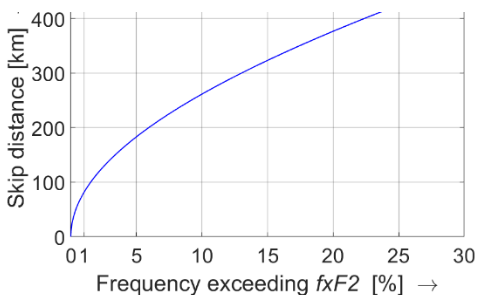

Fig. 4 Relationship between transmit fequency and fxF2 and the resulting skip distance.

A. Critical frequency and Dead Zone

This could describe the Dead Zone phenomenon very well, but only if the transmit frequency was exactly 0.5% higher than *fxF2*. However, the latter is not constant, and this situation would be short-lived. It would quickly be followed by either restoration of full coverage (with rising *fxF2*) or complete loss of signal in the entire coverage area up to 500 km (with falling *fxF2*). It is therefore more likely that at a particular transmit frequency there is either no coverage at all, or contiguous coverage up to 500 km. Mitigation of loss of propagation in this scenario is simple: switching to a lower transmit frequency will restore full coverage. Of course, this is only possible when the antenna efficiency at the lower frequency is sufficient to overcome the higher ambient noise level.

B. Happy Hour propagation near the equator: a special case

Near the magnetic equator, the polarizations of the ordinary and extraordinary wave become highly elliptical, or even close to linear, with their main axes aligned and perpendicular to the magnetic field. Normally, with a random orientation of the T2FD antenna, both waves will be excited. However, if the T2FD antenna is oriented perpendicular to the polarization of the extraordinary wave, only the ordinary wave will be excited. As only the extraordinary wave propagates during the 'Happy Hour' [25], the radio link would be lost during that interval. However, this does not change the discussion concerning transmission above the critical frequency. The same effects will be observed, except that the minimum distance will now follow the critical frequency of the ordinary wave *foF2*, which is slightly lower than *fxF2*, the critical frequency of the extraordinary wave.

Therefore, it must be concluded that transmission above the critical frequency is not a likely cause for the Dead Zone problem that was reported.

V. Impact of Antenna Characteristics

In Section II, we assumed lossless and isotropic antennas. In reality, the antenna characteristics directly affect the radio link. A block diagram of the radio link is given in Fig. 6. The coupling into and out of the skywave propagation path depends on the vertical radiation pattern of the antennas and their directivity $D(\alpha)$. The coupling to the ground wave path is represented by k_{gw}. We have seen that the groundwave couples primarily with the vertically polarized component of the radiation of the antenna. As the ambient noise is considered to come from all sides, the directivity of the receive antenna has no influence and therefore its directivity is taken as 1. The antenna efficiency η affects all signals, as well as the noise.

To investigate the impact of the antenna characteristics on the field strength, we assume a typical humanitarian radio communication link, consisting of a coordination center located in a hospital that communicates with a mobile field crew in an ambulance. The coordination center uses a Terminated 2-wire folded dipole (T2FD) antenna, a wideband wire antenna, and the field crew uses a short vertical whip antenna mounted at the front of the car, as was depicted in Fig. 1.

A. The T2FD antenna

The T2FD antenna is widely used by humanitarian organizations, NGO's (non-governmental organizations), banks, embassies and military organizations, mainly because of its wideband characteristics. It consists of a 2-wire or 3-wire folded dipole that is terminated in a resistor, as shown in Fig. 7. Due to the resistive load, it exhibits a relatively constant impedance over a large frequency range and provides a perfect match to the output stages of the transmitter. The wideband impedance match is often mistaken as a measure of the overall performance of the antenna. However, the radiation efficiency of the T2FD varies significantly with frequency, as does the radiation pattern. Both the antenna length and the height above ground determine the vertical radiation pattern [7]. Several versions of the antenna exist, of which the longer ones are better suited for the lower frequencies. The antenna can be extended

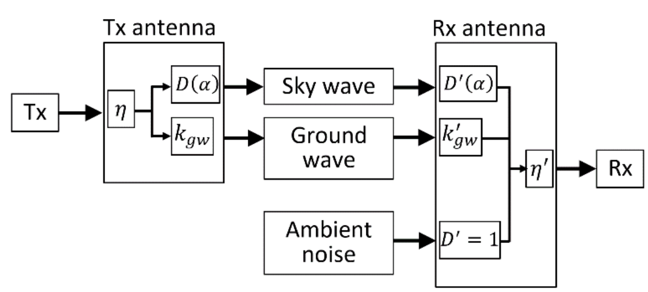

Fig. 6 Block diagram of the radio link (single-ended).

horizontally between two supports, or in an 'inverted vee' fashion from a single support. Here we will assume a horizontal 37 m (120 ft) long T2FD, suspended horizontally 12 m above ground. The vertical radiation pattern, simulated with NEC-5 method of moments software [26], is presented in Fig. 8. At high elevation angles, the antenna directivity is 4.5 dBi on 9 MHz and 7.1 dBi at 3 MHz. The antenna efficiency η is -2 dB at 9 MHz and -11 dB at 3 MHz. The coupling factor to the ground wave propagation path was already included in the simulations in Section II.

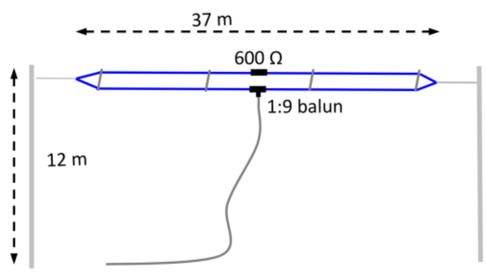

Fig. 7 Terminated 2-wire folded dipole (T2FD) antenna, suspended horizontally, 12 meters above ground.

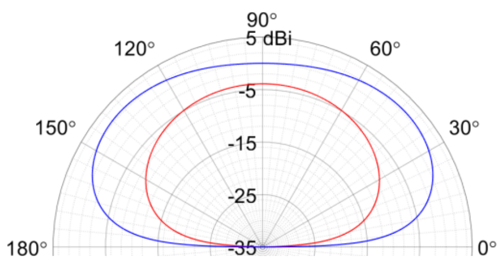

Fig. 8 Antenna gain versus elevation angle of a 37 m (120 ft) long T2FD antenna, 12 m above average ground (σ = 5 mS/m, ε_r = 13). The blue curve is for 9 MHz, the red curve is for 3 MHz.

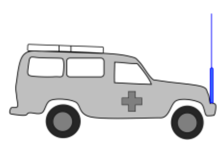

Fig. 9 A 2.4 m long vertical whip antenna mounted on a 4-wheel driven ambulance vehicle.

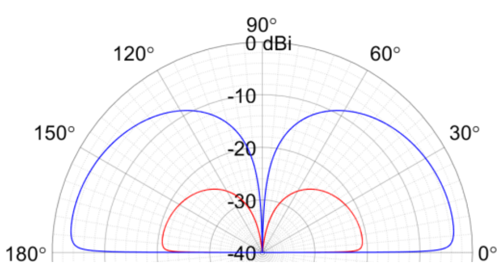

Fig. 10 Antenna gain versus elevation angle of a 2.4 m long vertical whip antenna above average ground (σ = 5 mS/m, ε_r = 13). The blue curve is for 9 MHz, the red curve is for 3 MHz.

B. The car whip antenna

The antenna of the mobile crew reporting the Dead Zone consists of a 2.4 m long whip, mounted on the front of a Toyota Landcruiser ambulance vehicle, see Fig. 9. Due to its small size (0.02-0.08 λ), the radiation resistance of the whip is low and it decreases quadratically with decreasing frequency. The car body is the counterpoise of the antenna, and impedance matching is achieved with a compact antenna tuning unit (ATU) directly underneath the whip. The radiation efficiency is determined by the ratio of the radiation resistance and the ohmic losses in the ATU, the car body and the ground. These losses in turn increase rapidly when decreasing the frequency, resulting in poor efficiency at low frequencies. The whip antenna has been simulated as a vertical radiator above average ground. The directivity of the antenna for low angles is approx. 4.5 dBi. Losses are estimated at 2 ohms at 9 MHz and 20 ohms at 3 MHz. With these values, the antenna efficiency η is -7 dB at 9 MHz. At 3 MHz, the efficiency is -25 dB, which is very poor. The antenna efficiency will affect both wanted signal and ambient noise, but not their ratio. However, as soon as the ambient noise power at the receiver input becomes lower than the receiver noise, the SNR will decrease. The vertical radiation pattern, simulated using NEC-5, is shown in Fig. 10. The sharp null overhead makes this antenna not very well adapted for short range skywave propagation. This corresponds with measurements published by Hagn [27].

C. Antenna response versus distance

Using formula (6), we can convert the radiation patterns in a graph relating antenna gain with distance. As can be seen in Fig. 11, the radiation pattern of the T2FD antenna is excellent for short distance ionospheric radio, but the radiation pattern of the whip antenna is unfavorable for short distance sky wave propagation. Also, at lower frequencies the antenna efficiency becomes very low. By multiplying the radiation patterns of both antennas with the received power given in Fig. 2, we obtain the received power in this scenario with real antennas. This is shown in Fig. 12. It can be seen that even on 9 MHz, were the whip antenna is more efficient, the SNR will be less than 10 dB in an area that is just outside the ground wave coverage, approximately between 5 and 25 km from the hospital. This zone expands when the frequency is lowered. At 3 MHz, coverage has become poor in the entire coverage area. This picture is actually optimistic, as the noise level will also increase with decreasing frequency.

Therefore, we may conclude that the vertical whip antenna is a likely cause of the Dead Zone effect.

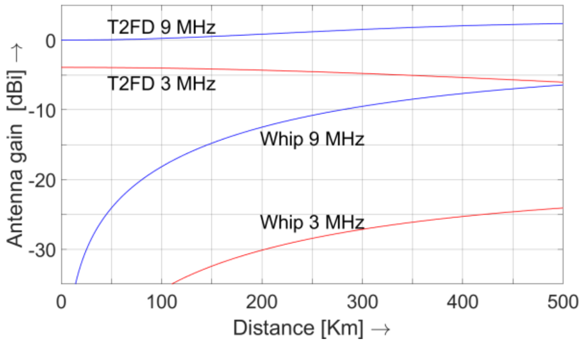

Fig. 11 Antenna gain versus distance for the T2FD and the whip antenna.

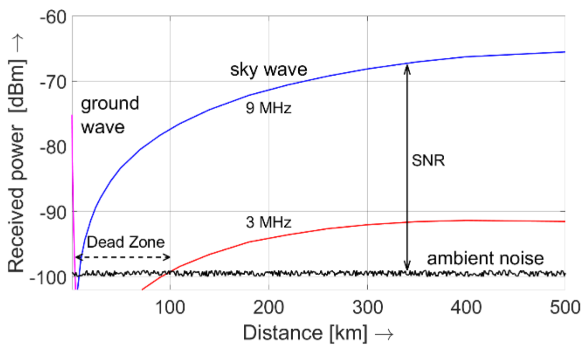

Fig. 12 Ground wave, skywave and radio noise for a 100-Watt transmitter, under the same conditions as in Fig. 2, but now with realistic antenna parameters added.

VI. Discussion and conclusions

Based on the investigation described in the previous sections, we can now analyze the possible causes and drivers of the Dead Zone and their probability. Firstly, good coverage can be achieved in the entire area up to 500 km when antennas are used on both ends of the radio link that radiate at steep elevation angles, typically between 50° and 90°. A 100-W transmitter and 0 dBi antennas will produce an SNR of at least 30 dB in a 2.4 kHz bandwidth.

We have seen that it is unlikely that ambient electro-magnetic noise is the cause for the Dead Zone, as its effect would be localized. Theoretically, it is possible that the reported Dead Zone could be created when a transmit frequency is selected that is between 0 and 0.5% higher than the critical frequency of the ionosphere. However, that condition would be very short-lived and is unlikely to repeat regularly.

When we investigate the impact of antennas typically used by humanitarian organizations and NGO's, we can reproduce the lapse in coverage when driving with a vehicle from the hospital outwards. In the first kilometers, ground wave coverage provides communication, but that signal attenuates quickly. In the next 20 km (at 9 MHz, more on lower frequencies) the signal disappears into the noise, to reappear at greater distances, quickly increasing to comfortable levels. The vertical radiation pattern of the vertical whip antenna is fully responsible for this effect.

A. *Mitigation measures*

With the results of this investigation, the HF radio-communication in remote areas can be improved. As we have seen that the vertical antenna pattern and the antenna efficiency of the antennas are the main factors, there are several ways out of the Dead Zone scenario:

- The first and more elegant solution would be to fit the vehicle with an antenna that radiates at steep angles, such as a rooftop loop antenna. While their efficiency is also low, they do not have a null in their radiation pattern, which results in 20 dB gain over the whip antenna at steep angles. This solution is common in military communications, but it is not yet popular in humanitarian circles, as the roof area needed to install such an antenna conflicts with logistical purposes of the car roof.
- Extending the whip antenna with a flexible section bent towards the back of the car is often thought to be a solution. The greater length of the radiating element will increase its radiation resistance and hence improve its efficiency, which will help improve the signal strength. However, research by Hagn [27] shows that vertical radiation remains poor. Also, the durability of such an antenna in harsh field environments seems to be wanting.
- Alternatively, increasing the antenna gain at the fixed location would also improve the signal strength. Installing a better antenna at a fixed locations is much easier than at the vehicles, and has to be done only once to serve a large number of mobile teams. A horizontal 'Lazy H' antenna, a broadside array of two full-wave dipoles space 0.375 λ to 0.75 λ apart, would yield substantial gain over a T2FD antenna, over a large frequency range, and could make up for part of the losses of the mobile antennas.
- Finally, installing the T2FD as an Inverted Vee antenna, or sloping it, will increase the vertically polarized component and so increase the ground wave component. This has a negative side-effect, however, as interference between the sky wave and ground wave will cause 'fading' in the transition zone, rapid fluctuation of the signal strength. This would therefore create another problem, although maybe a lesser one.

These solutions are independent of the geographical location and the topology of the terrain.

VII. Suggestions for further research

In this paper, several assumptions had to be made to analyze the problem. While these assumptions are realistic, they have not been verified by measurement yet. This investigation must therefore be seen as an initial assessment, which will help to focus such verification experiments and measurements. It would be worthwhile to precisely characterize: (a) the local electromagnetic noise level, (b) the diurnal profile of the path loss, (c) the efficiency of the whip antenna; (d) the vertical radiation pattern of the whip antenna including the influence of the car body; (e) the efficiency of the T2FD antenna for high elevation angles. For the last item (e), the method described in [7] may be used. Each of these items must be assessed as a function of frequency. Field measurements to objectively document the Dead Zone problem, with the associated ionospheric parameters, would also be valuable. Research into mitigating solutions is ongoing and will be subject to a separate publication.

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References

[1] R. Bown, "Transoceanic radiotelephone development," Proceedings of the Institute of Radio Engineers, 25.9 (1937): 1124-1135.

[2] E. Appleton, and W. J. G. Beynon, "The application of ionospheric data to radio communication problems: Part II," Proc. Phys. Soc., 59.1 (1947): 58.

[3] H. T. Friis, and C. B. Feldman, "A multiple unit steerable antenna for short-wave reception," Proc. IRE, 25.7 (1937): 841-917.

[4] H. H. Beverage, and H. O. Peterson, "Diversity receiving system of RCA communications, inc., for radiotelegraphy," Proc. IRE, 19.4 (1931): 529-561.

[5] M. Schwartz, and J. Hayes, "A history of transatlantic cables," IEEE Communications Magazine, 46.9 (2008): 42-48.

[6] J. A. Betts, "International communication: satellites and submarine cables," Electronics & Power, 15.7 (1969): 234-238.

[7] B. A. Witvliet, et al., "Near vertical incidence sky wave propagation: elevation angles and optimum antenna height for horizontal dipole antennas," IEEE Antennas and Propagation Magazine, 57.1 (2015): 129-146.

[8] “Handbook for Emergencies,” 3rd edition, UNHCR, Geneva (2007).

[9] “USAID-funded Community Resillience in Central Africa”, Annual report, year 2, Invisible Children (2019).

[10] J. M. Maso, et al., "Study of NVIS channel for USN protocol definition in Antarctica," Electronics, 9.6 (2020): 1037.

[11] R. M. Alsina-Pagès, et al., "Physical layer definition for a long-haul HF Antarctica to Spain radio link," Remote Sensing, 8.5 (2016): 380.

[12] K. G. Budden, “The propagation of radio waves: the theory of radio waves of low power in the ionosphere and magnetosphere,” Cambridge University Press (1988).

[13] J. D. Kraus, “Electromagnetics,” 4th Ed., McGraw-Hill, New York, USA, (1992): 686.

[14] NTIA, “Trusted Propagation Models Help Expand Commercial Wireless Services,” https://www.ntia.doc.gov/blog/2020/ntia-trusted-propagation-models-help-expand-commercial-wireless-services-0, downloaded 10 May 2021.

[15] P. G. Richards, D. Voglozin, “Reexamination of ionospheric photochemistry,” JGR: Space Physics, 116.A8, (2011).

[16] B. A. Witvliet, R. M. Alsina-Pagès, “Radio communication via Near Vertical Incidence Sky wave propagation: an overview,” Telecommunication Systems, 66.2, (2017): 295-309.

[17] O. S. Oyekola, “Comparisons of foF2 with IRI model and equatorial vertical drifts,” Advances in Space Research, 48.8, (2011): 1318-26.

[18] PropLab Pro V3, Solar Terrestrial Dispatch, http://shop.spacew.com/index.php/product/proplab-pro-hf-radio-propagation-laboratory/

[19] B. A. Witvliet, E. van Maanen, M. J. Bentum, C. H. Slump, R. Schiphorst, “A novel method for the evaluation of polarization and hemisphere coverage of HF radio noise measurement antennas,” in Int. Symp. On EMC, (2015): 289-294.

[20] J. D. Kraus, “Antennas,” 2nd Ed., McGraw-Hill, New York, USA, (1988): 766.

[21] “Radio noise,” Recommendation P.372-14, International Telecommunication Union, Radio Sector, Geneva, (2019).

[22] D. F. Martyn, R. O. Cherry, and A. L. Green, "Long Distance Observations of Radio Waves of Medium Frequencies," Proc. Phys. Soc., 47,2, (1935): 340-351.

[23] L. F. McNamara, “The ionosphere: communications, surveillance, and direction finding,” Krieger Publishing Comp., (1991): 168.

[24] B. A. Witvliet, E. van Maanen, G. J. Petersen, A. J. Westenberg, “Impact of a Solar X-Flare on NVIS Propagation: Daytime characteristic wave refraction and nighttime scattering,” IEEE Antennas and Propagation Magazine, 58.6, (2016): 29-37.

[25] B. A. Witvliet, et al., “Measuring the Isolation of the Circularly Polarized Characteristic Waves in NVIS Propagation,” IEEE Antennas and Propagation Magazine, 57.3, (2015): 120-145.

[26] G. J. Burke, “NEC-5 validation manual,” LLNL-SM-791163, Lawrence Livermore Nat. Lab., Livermore, Cal., USA, (2019).

[27] G. H. Hagn, J. E. Van der Laan, “Measured relative responses toward the zenith of short-whip antennas on vehicles at high frequency,” IEEE Transactions on Vehicular Technology, 19.3, (1970): 230-6.