HF Communications: Past, Present, and Future

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Abstract: High frequency (HF) communication, commonly covering frequency range between 3 and 30 MHz, is an important wireless communication paradigm to offer over-the-horizon or even global communications with ranges up to thousands of kilometers via skywave propagation with ionospheric refraction. It has widespread applications in fields such as emergency communications in disaster areas, remote communications with aircrafts or ships and non-light-of-the-sight military operations. This tutorial article overviews the history of HF communication, demystifies the recent advances, and provides a preview of the next few years, which the authors believe will see fruitful outputs towards wideband, intelligent and integrated HF communications. Specifically, we first present brief preliminaries on the unique features of HF communications to facilitate general readers in the communication community. Then, we provide a historical review to show the technical evolution on the three generations of HF communication systems. Further, we highlight the key challenges and research directions. We hope that this article will stimulate more interests in addressing the technical challenges on the research and development of future HF radio communication systems.

Keywords: HF communications; skywave propagation; ionospheric refraction; cognitive radio; artificial intelligence

I. INTRODUCTION

High frequency (HF) communication is an effective long-distance wireless communication paradigm, which can offer over-the-horizon communications and avoid the relatively high costs, vulnerabilities, and sovereignty concerns of satellite communications [1]. HF communication has been widely used in various fields such as military operations, emergency communications in disaster areas, aircraft or ships out of range of line-of-sight radio networks, distant regions lacking other communications, to name just a few [2].

During the past decades, there have been many interesting technical advances in research and development of HF communications, however, new critical challenges are emerging with ever-increasing requirements such as higher data rates, lower link establishment latency, intelligent anti-jamming capability, and diverse services, etc. On the other hand, recently, we have witnessed great achievements in other wireless communications, such as the fifth-generation cellular

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This article presents a general tutorial on HF communications.

communications [3], [4] and cognitive communications [5], [6]. Novel concepts, new architectures and powerful algorithms are blooming, which show great potentials to facilitate the research and development of next generation HF radio communications.

Motivated by the observations above, in this article, we present a short tutorial on the past, present, and future of HF communications. Specifically, we first present brief preliminaries of HF communications in Section II to facilitate general readers in the communication community. Then, in Section III we provide a historical review to show the technical evolution on the three generations of HF communication systems. Further, we highlight the open issues and research directions in Section IV, followed by conclusion in Section V. We hope that this article will stimulate more interests in research and development of future HF communication systems.

II. Brief Preliminaries on HF Communications

Generally, the HF band refers to frequencies between 3 and 30 MHz, although in certain cases, frequencies as low as 1.5 MHz can also be used for HF radio communications [1]. With the wavelengths ranging from 10 to 200 meters, the physical size of HF antennas will be comparable to the wavelengths of the radio waves it handles. Thus, the HF antenna can be quite large, and is often the most visible element of an HF radio communication system [2].

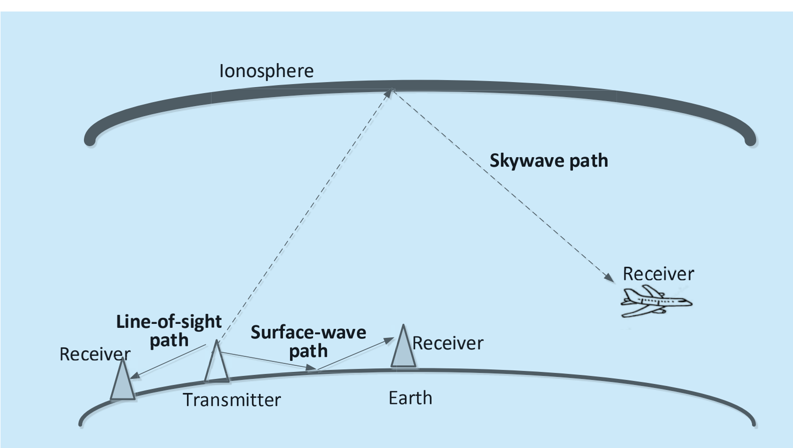

Fig. 1. *Illustration of HF radio communications.*

The key to achieving the potentials of HF radio communications lies in understanding and exploiting the basic physics of the HF channel. As shown in figure 1, HF radio signals mainly have three kinds of propagation modes: line-of-sight propagation, surface-wave propagation and skywave propagation. In the surface-wave propagation, an HF radio signal propagates over the earth surface with absorbtion and reflection, resulting in an “attenuated, delayed, but otherwise undistorted version of the transmitted signal” at the receiver [8]. In practice, the HF surface-wave propagation is useful over ranges up to a few hundred miles over sea water and a relatively shorter distance over land. A useful rule of thumb for attenuation versus distance for surface-wave propagation can be found in [8]. To enable over-the-horizon or even global communications with ranges up to thousands of kilometers, HF skywave propagation is well known as a promising paradigm via ionospheric refraction: an HF transmitter launches signals skyward, which interact with the ionosphere[1] and return to Earth far beyond the horizon. Notably, in certain cases, a multi-hop path between a pair of HF transceivers might be used where HF radio signals are refracted by the ionosphere and scattered from Earth's surface several times on the path [9].

[1] The ionosphere lies between about 70 and 600 km above Earth's surface and is an outer region of Earth's atmosphere with significant free electron density that varies with height.

HF skywave channel is well known as one of the most sophisticated and challenging wireless channels that exhibits temporal effects over a wide range of time scales and generally modeled as a superposition of the following effects [10]:

- *Long-term effects*: hourly diurnal variations in ionospheric propagation and so on up through the 11-year sunspot cycle. This category of effects has been captured in the models used in ionospheric propagation prediction programs, such as VOACAP [11] and ICEPAC [12].
- *Intermediate-scale instabilities*: fading effects on the order of seconds to minutes due to ionospheric motion, Faraday rotation

and similar phenomena. Statistically, the signal strength due to this kind of effects is lognormally distributed [13].

- *Shortest-term effects*: multi-path spreads on the order of milliseconds which produces Rayleigh or Rician fading, usually represented using the Watterson model [14].

The HF skywave channel is non-stationary on nearly any time scale. Any attempt to send data over such paths must carefully address the time-varying and dispersive nature of this channel at appropriate points in the HF transmitting and receiving systems.

III. Historical Review of HF Communications

The history of radio communications goes back more than 100 years. Around 1985, Marconi and other radio pioneers began to use long wavelengths for enabling long-distance commercial radiotelegraph communications with ships at sea where the wavelengths could reach thousands of meters and the input power should be hundreds of kilowatts. Shorter wavelengths (200 m or less) like HF bands were seemed to have little commercial value and granted to radio amateurs for experiments use until 1921 [15], when the HF band's long-distance transmission capability with significant lower transmit power and much smaller antennas was discovered. Since then, the research and development of HF radio communication systems have evolved for three generations and that for the fourth generation is ongoing, as summarized in figure 2. Generally, the basis on the division on the four generations of HF is from the technical evolution perspective. For any new generation over the previous one, there should be several technical breakthroughs or revolutions as discussed below. The time range of each generation are correspondingly specified.

3.1 First generation HF communications (1920s-1970s)

The earliest HF radio signals are based on spark gap transmitters which evolved from Hertz's original experimental apparatus in which stored energy was discharged across a spark gap within a tuned circuit. As the number of radios grew rapidly in the early twentieth century, the "dirty" transmissions from spark gap transmitters readily interfered with the reception of other wireless signals [16]. Thus, the need for narrowband HF radios attracted great research efforts which promoted the quick development of new HF transmitters. Notably, the invention of continuous wave oscillators offered stable and narrowband carriers for the on-off modulation used in radiotelegraphy and for the amplitude modulation used in radiotelephone that can transmit voice wirelessly in a 3-kHz channel. Since then, spectrum in the HF band is normally allocated in 3-kHz channels and the following HF technologies have therefore evolved to work within this narrow bandwidth. With the steady advance of technology, continuous wave was gradually replaced by frequency shift keying (FSK) waveforms and more complex modulation techniques such as binary FSK, M-ary FSK, M-ary phase shift keying (PSK), and M-ary quadrature amplitude modulation (QAM) that offered significantly better performance over HF channels.

For several decades, HF skywave communication was used as a dominating approach to provide long-distance communication services, where one of the key challenges was finding an usable frequency that could support the desired voice service as the usable frequencies vary with the time of day, the seasons, the space weather, and the locations of the stations. In the first generation HF communication systems, the usable frequencies were *manually* selected by highly-skilled radio operators but didn't provide full-time favorable reliability.

Notably, in the 1960s, satellites are introduced as an alternative for over-the-horizon communications that are more reliable and can provide much higher data rates over microwave bands of much wider bandwidth. There was a clear trend that satellite communications gradually dominated the over-the-horizon communications and took over most services of HF radio communications.

3.2 Second generation HF communications (1980s-1990s)

HF radio communication found its values again in 1980s mainly for two reasons. One lied in the fact that the emergence of attack and destroy weapon on satellite makes the unique advantages of HF radio communications more clear, for example, the robustness to jamming and vulnerabilities due to undestroyable ionospheric layer, the flexility of deployment, the relatively low costs, and long-distance point-to-point communication without relaying, etc. The other owed to the tremendous technical advances, especially, the introduction of microprocessors in automating the operations of HF radio communications and the transfer from analogy communications to digital communications with many breakthroughs of digital signal processing techniques.

One key feature of the second generation (2G) HF radio communication systems was *automatic*. In the late 1970s and early 1980s, engineers at leading HF radio companies began to employ microprocessors not only to provide powerful computing capability in the designed radios, but also to control the process of finding usable frequencies, which are formally termed as automatic link establishment (ALE). ALE made the use of HF radios easier. In the early 1980s, manufacturers independently developed their own approaches to ALE. In 1984, the MITRE corporation undertook a study of U.S. government's existing and planned HF radio networks and reported that the various proprietary systems are noninteroperable and they could not establish links with each other [17]. Then, the MITRE corporation was asked by National Communication System, an U.S. federal agency, to develop a federal standard for HF ALE. The MITRE engineer, Gene Harrison, worked with other leading engineers, merged many best ideas to form a new standard, FED-STD-1045 [18]. The U.S. Department of Defense then adopted the same technology as a new Appendix A to MIL-STD-188-141A [19]. Generally, the original ALE technologies developed independently by industry were considered as first generation ALE and the standardized, interoperable system in MIL-STD-188-141A and FED-STD-1045 was now called the second generation ALE.

By the mid-1990s, the standard ALE system had become notably successful and the use of ALE made HF radio naturally grew rapidly. Concerns began to grow over the increasing congestion of the very limited number of HF frequencies available worldwide. The shortcomings of the ALE system being used were gradually noted [9]: (i) The ALE system's asynchronous operation mode requires a lengthy scanning call (tens of seconds or even longer). (ii) The automatic channel selection requires that all stations that may be called must transmit sounds on every channel, which increases the number of frequencies scanned; (iii) The ALE system was originally designed to support voice service and thus lack of capability for data transmission. (iv) The advances in digital signal processing technology in the 1990s were not well incorporated. Thus, it was clear that a new generation of ALE technology was needed.

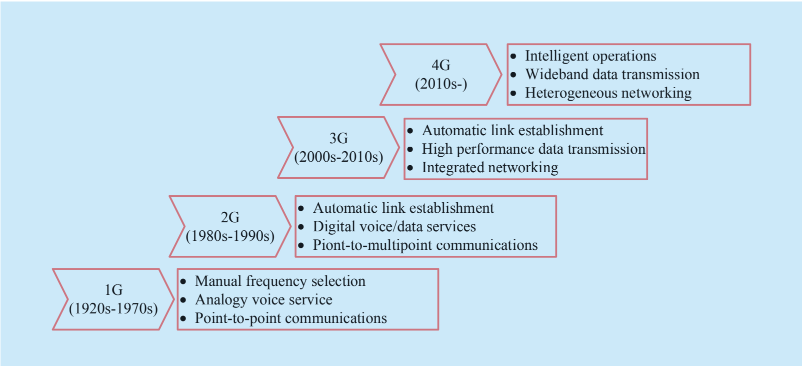

Fig. 2. *The evolution of HF communications.*

3.3 Third generation HF communications (2000s-2010s)

The goals of the the third generation (3G) HF radio communication systems were to link faster and at lower SNR, to carry more traffic, and to support larger networks. Quantitatively, the 3G technology was to achieve order-of-magnitude improvements over the second generation technologies in three aspects [1], [9]: (i) reduce the SNR required to set up a link by 10 dB; (ii) accommodate 10 times as many stations in a network; and (iii) improve data traffic throughput in a network tenfold in the same amount of spectrum.

In the first decade of the new century, the above new requirements motivate the HF research and management agencies to redesign the ALE technology. Compared with the second generation ALE, the third generation ALE can link faster and more robust, mainly due to the following advances:

- The synchronous operation mode of 3G ALE reduces the long scanning calls in 2G ALE with asynchronous operation mode.
- The 3G address is of fixed size and about half of the shortest 2G address, which results in shorter PDU and thus calling faster.
- The channels for link establishment and for traffic communications are separated, which improve the efficiency of the whole network.
- Various collision-avoidance mechanisms are introduced in the link establishment protocol to reduce the calling failure rate.
- The burst waveforms used in 3G ALE improve above 10 dB reliability over the 8-FSK used in 2G ALE.

The most well-known standard 3G ALE protocol is MIL-STD-188-141B, which not only provided the advanced version of the key functions of link quality analysis, ALE and automatic link maintenance, but also introduced both the functions of high rate data link and low rate data link. Moreover, the third generation HF radio communication systems can enable high performance data transmission, support larger networks via effective networking and provide *integrated* services, from analogy and digital voices to circuit and packet data traffic.

3.4 Next generation HF communications (2010s-)

With the 3G systems being matured, worldwide research interests began to focus on developing the next generation HF radio communications, where the key features have been recognized as *intelligent* and *wideband*. For one thing, the recent advances in artificial intelligence and machine learning are reforming the tractional designs of communication systems, where one representative example is that, during the past decade, we have witnessed the enormous research outputs of the cognitive radio technology with the key idea to empower a radio with a brain like human people to observe, plan, decide, and act. For another thing, the requirements of much higher data throughput and diverse services (such as images and videos) motivate the research and management agencies to consider the breakthrough of long-term usage of HF spectrum with 3-kHz channel. As a result, the recent standards like MIL-STD-188-141C and MIL-STD-188-110C can support HF channels as wide as 24-kHz.

IV. Overview of Key Challenges and Future Directions

Building on the discussions on historical trends, in this section we turn our attention to some of the key challenges and research directions that arise in HF communications.

4.1 Key challenges

1) Reliability: Perhaps the most significant and widely-discussed challenge for HF communications is how to build reliable connections between HF transceivers. This issue recently has become even more serious mainly due to the following reasons:

- Complex and unpredictable factors in natural environment, as mentioned in Section II, result in significantly fluctuating channel conditions over HF bands. Especially, the ever-changing ionospheric refraction leads to different usable frequencies over time.
- Unintentional interference are deteriorating HF electromagnetic environment and rising the background noise as large as tens of dB-Watt, due to uncoordinated use of HF bands

by users from different systems. In this context, it is well known that several decades ago, an HF transmitter with tens of watts transmit power could successfully enable long-distance wireless communications up to thousands of miles, however, nowadays an HF transmitter with higher transmit power and much advanced techniques cannot achieve reliable communications with the same distance.

- Intentional jamming has obtained increasing attention in the past few years that may be imposed for malicious purpose or military operations in electronic spectrum warfare or electromagnetic warfare. The strength of intentional jamming signals are usually very high for interrupting the normal desired HF connections.

2) High Data Rates: Another key challenge for HF communications is to provide high data rates for supporting image and video transmission. For many years, HF communication has been well recognized as a long-distance communication approach to provide voice and low-speed data transmission with channel bandwidth no wider than 3 kHz. Thus, it was not surprising that years ago HF communication was deemed to decline as competing satellite communication using microwave bands can provide over-the-horizon wireless transmission with relatively higher data rate. Currently, compared with satellite communication, HF communication still has its unique values for the relatively low costs, the robustness to jamming and vulnerabilities, the flexility of deployment, and long-distance communication without relaying. However, in most cases, it is treated as the minimum-guarantee method for long-distance voice and low-speed data transmission, but not the first choice for image or video transmission.

Recent years have seen that transmission of large files, surveillance video or common operating picture over HF links becomes essential. Thus, the old question rises again, "How can we achieve even higher data rates over HF bands?" Technical breakthroughs are needed to address this challenge.

3) Massive Remote Access: For several decades, point-to-point or point-to-multi-point long-distance communications have been the dominating pattern in HF systems. Nevertheless, as HF communications finds increasingly worldwide applications in both military and civil areas, more and more HF radios are equipped in ships, aircrafts, vehicles and kinds of Internet of Tings devices. Consequently, the number of concurrent HF connections will increase dramatically, which results in a critical challenge here named massive remote access. Here "massive" refers to the huge number of concurrent connections and "remote" means that the distance between HF transceivers is very large compared with other well-known communications such as cellular communications.

There are two key performance indicators in massive remote access that are of great interest: access delay and interference control. For most of the existing access control schemes, either random access schemes like carrier sensing multiple access (CSMA) or non-random access schemes like time division multiple access (TDMA), the average access delay of each HF radio increases linearly or even exponentially with the increasing number of concurrent HF connections. On the other hand, the contradiction between the limited spectrum of HF band and the increasing number of concurrent HF connections becomes more and more serious. Spectrum reuse in time, frequency, and/or space domains is necessary to address this contradiction while how to effectively control the mutual interference is one key challenge in reusing the HF spectrum.

4.2 Future directions

To address the technical challenges above, there are many open issues and research directions. In the following we just highlight several of them, as shown in figure 3,

1) Intelligent HF radio: From a historical perspective, there have been HF hardware radio, HF software (defined) radio and HF cognitive radio, sequentially. In this context, one key feature in the trend of research and development of HF radios is to improve their self-adaptability to ever-changing environment. The recent advances in artificial intelligence (AI), especially, machine learning and deep learning, presents a powerful toolbox to continue this trend and make future HF radios act much more smart. Several interesting directions are listed (but not limited to) the following:

- Proactive ALE with pre-selection of favorable frequencies based on spectrum prediction. It is well known that frequency selection is one of the critical task in HF communications since usable frequencies change with time. However, dynamic frequency selection from thousands of candidate frequencies involves an one-frequency-by-one-frequency scanning and sounding process that results in significant time delay. In this context, most of current HF systems restrict frequency selection only in a subset of all frequencies to achieve lower time delay at the cost of not always capturing the favorable or even usable frequencies. Spectrum prediction based on effectively mining the historical data poses a promising approach to provide pre-selection of favorable frequencies and shows good potential to make a balance between time delay and frequency quality.
- Smart anti-jamming by leveraging various machine learning approaches. In the future, both jamming and anti-jamming will become smart with the trend to integrate AI into the design of next generation communication systems. The jamming behavior becomes dynamic and intelligent which makes it nontrivial to estimate the jamming patterns and parameters timely. One interesting example is to exploit the spectrum waterfall information directly from an image processing perspective based on deep reinforcement learning [20].

2) Wideband HF: Wideband HF will continue to be a dominating future direction to increase data rates for supporting diverse services like image and video transmission.

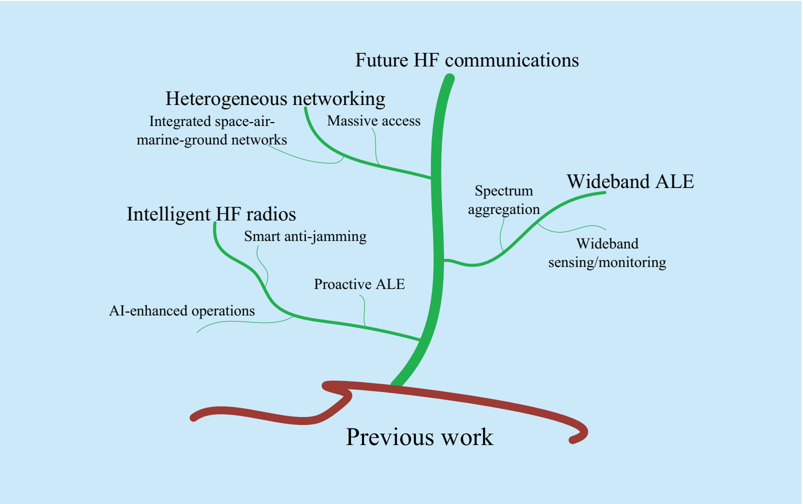

Fig. 3. *The research directions in shaping future HF communications.*

Historically, in the nominal HF band (i.e., 3- to 30-MHz), most channels are allocated only 3 kHz. There exist main three possible approaches for implementing wideband HF and achieving higher data rates:

- The first is to design new waveforms utilizing current 3-kHz allocations. One key variable available to optimize is the modulation density. To enable a bandwidth efficient modulation, Shannon's capacity theorem suggests that the cost in transmit power will be exponentially higher.
- The second is a multichannel approach by using multiple contiguous or noncontiguous 3-kHz channels. This approach offers uses a linear increase in data rate as a function of the number of channels available. Multichannel automatic repeat request protocol provides an
- The third is to increase data rates by using wider contiguous bandwidth waveforms. This approach considers the breakthrough of current usage of HF spectrum with 3-kHz bandwidth and offers promising potentials to improve the performance. The width of contiguous bandwidth can be pre-determined or adaptive, depending on the practical HF spectrum usage pattern and the implementation complexity.
- The fourth is to increase data rates by using wider noncontiguous bandwidth wave-

forms. Spectrum aggregation of noncontiguous channels is a challenging task for the design of both hardware and software of HF radios, however, useful when wider contiguous bandwidth is unavailable.

Notably, in narrowband HF applications, ALE is the key function of finding a usable frequency and setting up links between two or more radios. In wideband HF applications with new bandwidth flexibility, additional automated capabilities are necessary, such as wideband spectrum sensing/monitoring and multichannel spectrum coordination.

3) Heterogeneous Networking: The research of networking of HF radios is relatively few since point-to-point communications is the dominating usage pattern of the long-distance or even global HF communications. Most of existing studies on networking of HF radios focus on the coordination of point-to-multi-point communications. Several research directions are as follows:

- Distributed networking of multiple spatially-dispersed HF receivers to improve reliability by exploiting diversity combining [21].
- Centralized access control of HF radios to coordinate the concurrent massive connections by developing various random or non-random access techniques.
- Heterogeneous networking of HF communications and satellite communications, military networks and civil cellular communications to enable an integrated space-air-marine-ground communication network.

V. Summary

This article presents a general tutorial on HF communications. We first present brief preliminaries on the unique features of HF communications. Then, we provide a historical review to show the technical evolution on the three generations of HF communication systems. Further, we highlight the key challenges and research directions. We believe that there will be fruitful research outputs towards wideband, intelligent and integrated HF communications and hope that this article will stimulate more interests in addressing the technical challenges ahead.

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