HF Radio Mesh Networks

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***Abstract*— Wireless mesh networks provide robust connectivity among a number of nodes. The use of high-frequency radio links extends this concept beyond line of sight to provide potentially global coverage. In this paper, we explore the capabilities of HF radio mesh networks, and evaluate the performance of multi-hop beyond-line-of-sight networking in both local (NVIS and surface-wave)) and long-haul applications. Two alternative channel access technologies are compared: automatic link establishment and fixed-frequency MAC protocols. The data handling capacity of HF radio mesh networks is computed as a function of the path length through the mesh network (a key metric in line-of-sight mesh networks) and as a functino of number of nodes.**

***Index Terms*—HF radio communication, communication system routing, wireless LAN, mobile communications.**

I. Introduction

HIGH Frequency (HF) radio operates at carrier frequencies that potentially propagate to any point in the world via one or more "reflections" from the ionosphere. However, such "skywave" links are subject to complex interactions among the solar and terrestrial environments, and the ability to communicate directly between arbitrary pairs of points via HF may not be reliable under all conditions.

Despite the uncertainty of connectivity, the ability to communicate over thousands of kilometers without the need for expensive terrestrial or orbiting infrastructure has made HF radio a popular and valuable technology since the early 20th century, and new technology is continually being developed to improve the reliability of HF radio communications.

1) Advanced signal processing has been introduced to cope with the fading and inter-symbol interference of HF channels, and to increase the data rates on these narrowband (usually 3 kHz) channels [1].
2) Link management protocols have automated the task of finding usable frequencies [2].
3) Medium access control (MAC) protocols have been developed for sharing scarce spectrum [3].
4) Data link protocols specifically evolved for the channel and modem characteristics of HF links adapt to changing channel conditions to maintain data throughput near the maximum achievable from minute to minute [4].
5) Relaying can extend reliable coverage worldwide [5].
6) Routing protocols for HF LANs adapt to dynamic connectivity with low overhead [6], [7].

The long and widespread use of HF radio for civilian, government, and military communications has identified several useful strategies for using HF radio:

1) *Skywave* operation employs the ionosphere to refract radio frequency energy back to Earth from altitudes of of up to a few hundred km. This beyond line-of-sight mode permits communication over ranges of thousands of km, but requires use of a frequency that will propagate under the instantaneous ionospheric and terrestrial conditions (see next section). At some operating frequencies, communication with nearby nodes may not be possible, because those frequencies penetrate the ionosphere at the steep takeoff angle required for short-range communication. The range of excluded locations is called the "skip zone."
2) *Surface wave* operation does not employ ionospheric refraction, resulting in a range that does not extend much past the horizon. The Extended Line-of-Sight range is a few hundred kilometers over sea water, less over land. Surface wave coverage does not suffer from a skip zone, but is limited by terrain or man-made obstacles.
3) *Near-Vertical Incidence Skywave* (NVIS) operation is a special case of skywave operation that launches HF energy nearly vertically, with reflected energy coming back to the Earth's surface (nearly vertically) throughout the region surrounding the transmitter. This popular mode overcomes nearby terrain obstacles without a skip zone, but requires careful selection of antennas and operating frequency.

A. HF Automatic Link Establishment

One of the peculiar characteristics of HF radio skywave (including NVIS) propagation is a strong dependence of path loss on operating frequency. The highest useful frequency on a given point-to-point link is determined by the current ionization of the region(s) of the ionosphere at which the propagating wave is refracted. Frequencies above the critical frequency are not "bent" sufficiently to return to Earth, and so cannot be used for communication *over that path* and *at that time*.

Lower regions of the ionosphere dissipate the energy passing through them to and from the more ionized outer regions in which refraction occurs. This component of path loss is also frequency-dependent, and introduces a time varying lower bound on useful frequencies for each ionospheric circuit.

As a result of these upper and lower bounds, there is a "window" of usable frequencies for each pair of communicating nodes. This window varies with time of day, season, sunspot activity, latitude and longitude, and so on. Sophisticated models of ionospheric propagation have been developed over many years, and these are quite good at predicting the range of usable frequencies, except during extraordinary conditions. Current technology offers an alternative to the "open loop" models used in prediction programs: real time tracking of the window of usable frequencies for each HF link.

A popular method of finding and using the best frequencies is termed Automatic Link Establishment (ALE). An ALE system typically emits energy on each of a pool of assigned frequencies (termed "sounding"), and other nodes measure and record the arriving signal quality from each station on each frequency. This link quality database can then be used to select a frequency for use with any other node upon request.

When not engaged in traffic, ALE radios scan their assigned frequencies, listening for calls and sounds. An incoming call results in a handshake on the calling frequency (and possibly on a separate traffic frequency), after which the nodes involved commence voice communications or engage a data protocol. Thus HF ALE is an automatic frequency selection and traffic setup protocol.

B. HF Local Area Networks

With the potentially global range of HF radio links, the partitioning of HF networks into local area networks (LANs) versus wide area networks (WANs) is conventionally based on considerations other than distance. One partitioning approach notes that in many LANs all transmissions are assumed to reach all nodes (i.e., a broadcast medium is used). This is true for both wired (IEEE 802.3) and wireless LANs (IEEE 802.11). Of course, in a wireless LAN, some nodes may be "hidden" from other nodes, but the channel access protocol design is based on the ability of most nodes to hear each other.

When all nodes in an HF network are operating on a single frequency, we have an analogous situation to the WLAN, so this is termed an HF LAN. Current research in HF LANs has focused on efficient channel access protocols [3] and routing [6], [7] for networks operating with surface wave links.

In HF ALE networks, on the other hand, nodes that are not linked with a sending node A typically do not receive packets sent by A. Thus, by this definition, an ALE network is not a LAN, and this paper will treat ALE networks as distinct from HF LANs.

C. Mesh Networks

Mesh networks comprise an interesting class of multi-hop wireless networks with the following characteristics [8]:

1) Node placement is arbitrary, not chosen for optimum connectivity.
2) Omnidirectional antennas are used.
3) Routing is multi-hop: nodes must be prepared to relay traffic for each other. Some nodes may be connected to a fixed infrastructure, but fixed infrastructure is not the principal interconnection among mesh net nodes. Indeed, the purpose of the mesh network is usually to share connections to the fixed infrastructure with all member nodes.
4) Mobility is sufficiently low that routing can be optimized for throughput rather than for detecting and repairing broken links.

Some HF networks share these characteristics. For example, ship-shore HF networks have been estimated to have a diameter of one hop 75% of the time, two hops 20% of the time, and three hops 5% of the time. Other applications of HF networking are predominantly (90%) diameter two. The growing emphasis on net-centric operation in military applications, despite the lack of backbone connectivity to some nodes, leads naturally to the use of mesh networking to extend network access to tactical nodes. The inexpensive, beyond-line-of-sight reach of HF links makes it worthwhile to investigate whether research results for mesh networks using line-of-sight (LOS) frequencies could be useful in multi-hop HF networks.

Recent research [8], [9] has determined that LOS mesh networks are feasible for extending Internet access via multi-hop relaying, typically using IEEE 802.11 WLAN technology. Key findings are that throughput in such WLAN mesh networks tends to fall as the number of hops increases, due to interference, and that performance might be improved by using multiple frequencies in the network and multiple radios per node. These enhancements can be readily accomodated in HF networks, as discussed in the next section.

II. HF Mesh Networks

An HF mesh network could be formed by incorporating a routing protocol with either a network of ALE radios or one or more token-passing fixed-frequency rings:

- ALE inherently uses multiple frequencies, although only a subset of the ALE frequency pool will be usable for each link in a network.
- Each token-passing ring will normally operate on a single frequency so achieving multiple-frequency operation will require the linking of multiple rings to form the mesh.

Multiple radios per node would be required in a multi-ring token mesh so that relay nodes could simultaneously listen in all of their connected networks (which operate asynchronously). Although it is sufficient to have multiple receivers and a single transmitter in such relay nodes, the network could avoid delays in relaying if multiple transmitters are also available. Such multiple-radio HF nodes are used today in large fixed installations such as the US Air Force HF Global Communication System. The Joint Tactical Radio program envisions multiple radio instances in vehicular and even portable radios in the future (although co-location effects, antenna sharing, and so on may be problematic). For this investigation, we assume that multiple HF radios are available at each node.

A. HF Mesh using HF LAN technology

An HF mesh could employ the token-passing MAC [3] developed for naval surface-wave networks. Token passing rings are formed on the fly, and re-formed as necessary. To avoid interference, each ring would operate on a distinct frequency. Each node is assumed to have a separate radio for each ring in which it participates.

A clear advantage of a mesh of HF token LANs over LOS mesh networks is that neighboring nodes would not interfere with each other, and the unexpectedly rapid drop in throughput with path length seen in mesh networks such as Roofnet [8] would not occur.

B. HF ALE Mesh

An HF ALE mesh would not be as rigidly structured as a mesh of HF token rings, and would share its pool of frequencies using a contention-based (listen before transmit) channel access protocol. ALE sounding would provide the connectivity information normally obtained by the routing protocol (e.g., using Hello packet exchanges). Although multiple radios per node would not be required for an ALE mesh, previous work [10] suggests that having only a single radio per node becomes a bottleneck under heavy traffic loads.

III. Performance Analysis

In this section, analytical models for the performance of these two HF mesh network designs are presented, followed by simulation results in the following section.

A. *Performance of HF Token Mesh*

Each HF token ring operates as follows [3]:

1) A node may only transmit when it holds the token.
2) A node may transmit for up to a maximum token holding time t_{TH} before it must pass the token to its successor in the ring.
3) All nodes in a ring are assumed (for this paper only) to be connected directly to all other nodes in the ring, so relaying occurs only between rings.

An example token mesh is shown in Figure 1. The arrows show the successor-predecessor relationships in each ring. Note that one node acts as a gateway between rings 1 and 2, while two gateway nodes are shared between rings 2 and 3.

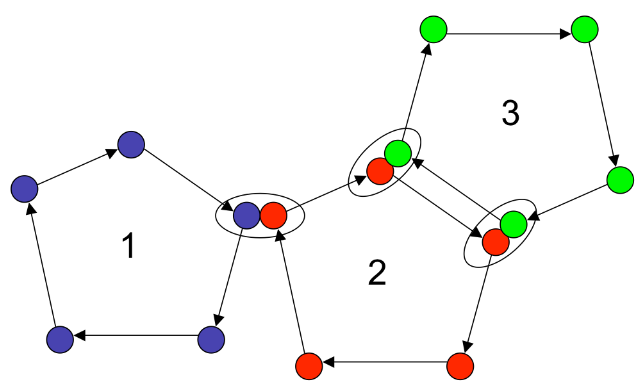

Figure 1: Example HF Token Mesh

The heavy arrows in Figure 2 depict message relay from source node S to destination D. A routing protocol (beyond the scope of this paper) has chosen gateway nodes A and C for this traffic. Relaying a traffic stream works as follows:

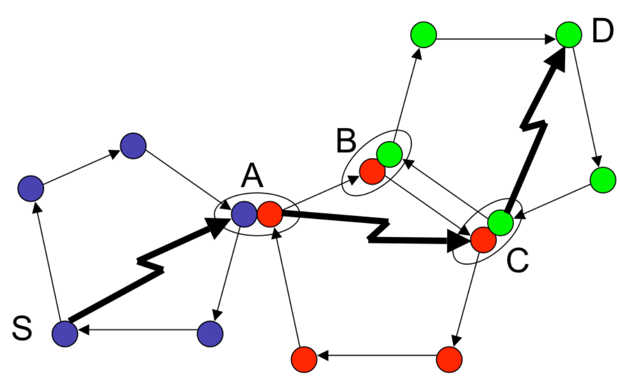

Figure 2: Message Relay in HF Token Mesh

1) Source node S transmits to node A for no more than the maximum token holding time t_{TH} each time it gets the blue token. Node S will transmit for less than t_{TH} if it exhausts its buffer, which occurs when the rate of the incoming traffic is lower than the saturation throughput of the blue ring.
2) Node A buffers this received traffic, sending it to node C in the red ring only when A holds the red token.
3) Node C likewise buffers the stream from A until it holds the green token, at which point it relays traffic to node D.

The follwing parameters are used in the analytical models in this section:

Symbol	Parameter	Typical Value
t_{TH}	Maximum token holding time	
t_u	User data time per token rotation	$\le t_{TH}$
t_{TP}	Token pass time	0.12 s
t_{TA}	Turnaround time (incl. crypto)	2 s
t_{ack}	Time to send data link ACK	0*
r_{data}	User data rate on air (after FEC)	

The time to send short control packets such as tokens and acknowledgments (ACKs) tends to be much shorter than the interleavers used with HF channels, so such control packets are often repeated enough times to fill an interleaver. In this case, doubling the data rate will simply double the number of times a control packet is sent, and the time to send a control packet is therefore independent of data rate. For the same reason, the time to send an ACK in addition to sending a token may be 0, as the ACK simply replaces half of the repetitions of the token within the interleaver.

Analysis of a single ring

First, consider a ring of N_1 nodes with a single source sending traffic to a destination in that ring. The token rotation time t_{cycle} is

$$t_{cycle} = t_u + t_{ack} + N_1\left(t_{TP} + t_{TA}\right)$$

and the throughput is

$$X = r_{data}\frac{t_u}{t_{cycle}} \le X_{\max} = r_{data}\frac{t_{TH}}{t_{cycle}}.$$

If we assume that traffic is produced in a steady stream at the source, the delay from the first bit of a packet delivered to the source node until it is delivered to the destination is depicted in Fig. 3:

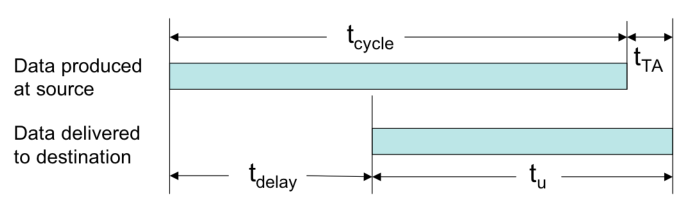

Figure 3: Delay in Single Ring

The last bit sent will be produced at the source just before the end of its token holding time, and will arrive at the destination after one turnaround time (processing time at sender and receiver plus propagation delay). The next cycle for producing data at the source begins immediately, so we have the timing relationship in Fig. 3, and t_{delay} is

$$t_{delay} = t_{cycle} + t_{TA} - t_u = t_{ack} + N_1\left(t_{TP} + t_{TA}\right) + t_{TA}$$

If S sources are sharing the channel, sending to multiple destinations (distinct from the sources), t_{cycle} becomes

$$t_{cycle} = S\left(t_u + t_{ack}\right) + N_1\left(t_{TP} + t_{TA}\right)$$

Analysis of rings in tandem

Now we generalize to an arbitrary number of rings, through which traffic is relayed. Each ring contains N_i nodes and operates with a data rate of r_i. Rings may operate at differing data rates due to propagation and noise characteristics that vary from ring to ring. The token rotation time t_{cycle} is

$$t_{cycle,i} = t_{u,i} + t_{ack} + N_i\left(t_{TP} + t_{TA}\right)$$

The saturation throughput for the tandem path is determined by the bottleneck ring b (usually the ring with the slowest data rate). When this ring is saturated, $t_u = t_{TH}$, and

$$X_{sat} = r_b \frac{t_{TH}}{t_{TH} + t_{ack} + N_b\left(t_{TP} + t_{TA}\right)}.$$

Note that the saturation throughput for an HF Token Mesh network is independent of the number of token rings through which traffic is relayed, due to the contention-free nature of the channel access protocol. The maximum throughput available to a single traffic stream flowing through tandem token rings is a function of the number of nodes N_b and the data rate r_b in the bottleneck ring, as shown in Fig. 4[1].

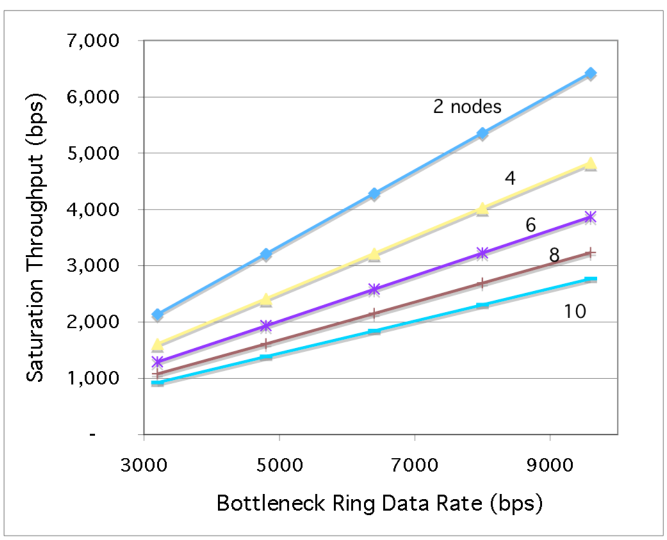

Fig. 4: Token Mesh Saturation Throughput

[1] In this figure, the timing parameters are typical of military HF systems: token holding time was set to 8.6 s, token passing time was 120 ms, and turnaround time was 2 s. ACK time is subsumed in the token pass time.

The nominal delay through R rings in tandem consists of the initial synchronization delay (from the single ring analysis) plus a resynchronization delay at each additional ring (half of that ring's cycle time, on average) plus a turnaround time to cross each additional ring. Since frames received with errors must be retransmitted, we must also include a factor n_i which is the average number of times each frame must be sent on ring i:

$$t_{delay} = Rt_{TA} + \left(n_1 t_{cycle,1} - t_{u,1}\right) + \sum_{i=2}^{R} t_{cycle,i}\left(n_i + 0.5\right)$$

B. *Performance of HF ALE Mesh*

An HF ALE mesh net relays traffic through an ad-hoc network of HF nodes as shown in Fig. 5. Note that connectivity in HF networks is not necessarily governed by geographic proximity; in some cases, distant stations can be easier to reach than nearby stations. In Fig. 5 the red nodes are all within NVIS range of each other; long-haul skywave links have been established between other pairs of nodes (color-coded by pairwise usable frequency) to form indirect routes.

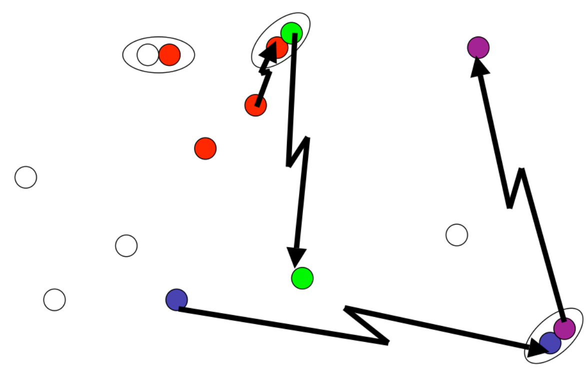

Fig. 5: ALE Mesh Net

The follwing parameters are used in the analytical models in this section, along with typical values for a third-generation HF ALE system (HDL protocol):

Symbol	Parameter	Typical Value
t_{data}	Data transmission time per cycle	9.7 s
t_{TA}	Turnaround time	250 ms
t_{ack}	Time to send data link ACK	1.3 s
r_{data}	User data rate on air (after FEC)	≤ 4800

An HF ALE mesh net could operate in either packet switched or circuit switched mode:

- In packet switched mode, ALE is used to set up a link for each packet and ACK, after which the link is released. This results in high overhead, but permits fine-grained sharing of frequencies.
- In circuit switched mode, ALE is used to set up a link before the traffic stream begins, but this link is then retained for the duration of the traffic stream (or until changing propagation requires intervention to change frequency). This is more efficient but blocks frequencies.

Analysis of circuit-switched ALE mesh networks

The simpler case to analyze is circuit-switched operation. Asymptotically, as the amount of traffic transferred on the circuit increases, the time required for link setup becomes insignificant, and the throughput on each link *i* approaches

$$X_i = r_{data} \frac{t_{data}}{t_{data} + t_{ack} + 2t_{TA}}.$$

As in the token mesh network, the link with the lowest data rate will be the bottleneck. Likewise, because ALE technology ensures that distinct frequencies are used for each link in the path, there will be no interference between links, and no dependence of throughput on path length. Circuit-switched ALE mesh network throughput as a function of bottleneck data rate (after code combining) is shown in Fig. 6.

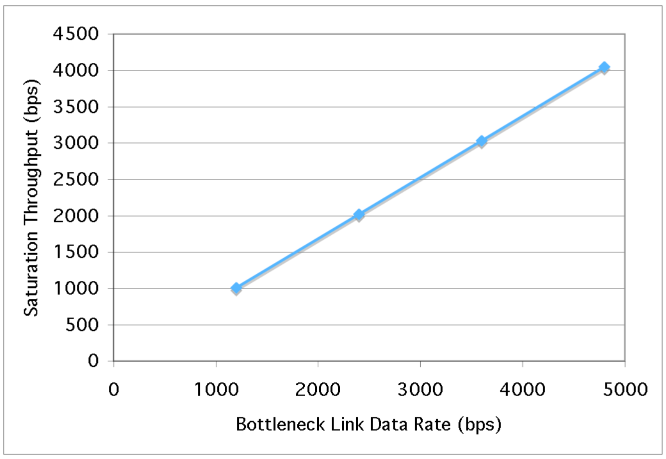

Fig. 6: ALE Mesh Net Circuit-switched Throughput

The delay through a circuit-switched 3G ALE mesh is approximately the sum of the data cycle times along the path. During each data cycle, several data packets (up to 24) are sent over the link. Each received data packet must be decoded at a relay node, forwarded to the relaying radio at that node (typically using a high-speed bus), then re-encoded and sent from that radio. Frames received in error must be resent over the incoming link, and each retransmission costs one synchronous cycle time. As in the token mesh analysis, we use n_i to represent the number of times (on average) a packet must be sent on link *i*. For a path of *R* linke, we have

$$t_{delay} = \sum_{i=1}^{R} t_{cycle,i}\left(n_i + 0.5\right)$$

IV. Conclusions and Future Work

A. Conclusions

Two example HF mesh network architectures were studied here, a mesh of token rings and a mesh of ALE nodes. Both naturally incorporate two of the key features identified for peak performance in mesh networks: multiple frequency operation and multiple radios per node.

The performance of the two mesh network designs was evaluated, focusing on the metric commonly used in evaluating LOS mesh networks: throughput for a single traffic stream. In both cases, the throughput of paths of arbitrary length through the mesh networks did not exhibit the significant degradation seen in LOS mesh networks. Delay through the mesh networks increased linearly with path length.

B. Future Work

Several aspects of HF mesh networks merit further study:

- The potential for interference among multiple traffic streams flowing through the mesh was not studied.
- An appropriate routing protocol needs to be developed.
- A multicast routing protocol would be especially valuable in military applications of HF mesh networks.

Both US and NATO planners are seeking wireless architectures that support net-centric operations. HF mesh networks appear to offer a valuable extension to the range of military mesh networking, so this technology could be considered for standardization if further studies continue to find good performance.

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