Modeling Automatic Link Establishment in HF Networks

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***Abstract*—Most High Frequency (HF) communications systems deployed on the field today implement ALE (Automatic Link Establishment) techniques in order to help the end-user automatically set up a link with good properties. Two generations (so called 2G and 3G ALE) have been standardized since the 90s, and are today being revisited due to the emergence of wideband HF waveforms. In this paper, we model ALE protocols using an abstraction model based on Markov chains. Our model captures faster and more easily than simulations the main characteristics of the ALE processes and the interactions between their numerous parameters. In that sense, this model constitutes a useful tool to help design and benchmark future ALE strategies. In order to validate the model, classical ALE simulations have also been carried out, that show the high similarity obtained with the model. We also show how to exploit the model to give insights on the limitations of current 2G ALE, for instance on the handshake method and on the impact of frequency selection strategy on the ALE duration.**

***Keywords*—High Frequency (HF), Link establishment, modeling, Markov chain.**

I. Introduction

HF radio communications have long been the only solution for wireless communications beyond line-of-sight (BLOS) with none or minimal infrastructure, which explains their importance in military communications. Supporting communications over several thousands of kilometers, HF propagation channel is however highly variable and error-prone. It tends to make HF communications unreliable and difficult to establish, especially when used with little or no knowledge of the propagation conditions.

ALE solutions have been historically developed to provide automation and ease of use to end-users having limited time or limited skills to operate HF communication systems. In practice, ALE-able radios are given a pre-defined and shared set of frequencies that are scanned for incoming calls by all stations in the same network when they are idle. Any station wanting to establish a link determines the first frequency it should use, based on a Link Quality Analysis (LQA) mechanism. The radio then begins its call and tries to establish a link with another radio. Obviously, this automatic (without human intervention) selection of a frequency between a caller and a called radio should be done as quickly as possible to allow the end-user to place his call and provide information (whether voice or data) to its correspondent.

Two generations of ALE standards, MIL-STD-188-141A [1] denoted as the ALE 2G and more recently the STANAG 4538 [2] co-exist on the field. A HF specific simulation framework and a comparison between 2G and 3G standards were proposed in [3] and [4] respectively. Their main findings is that 3G outperforms the 2G ALE in dense collision prone networks however the two protocols provide close results in large unidirectional networks, for instance BRASS-type naval scenarios. In the meantime, enhancing the performance of ALE mechanisms remains a tough challenge to overcome. Inspired by the recent progress in wireless networking and communication domains, several intiatives to improve the efficiency of existing standards and sometimes propose completely new solutions started to arise. These proposals rely on two different paradigms: i) exploring cognition instigated by the recent progress in the cognitive radio domain in order to learn and optimize selecting/exploiting the existing channels for communications [5], or ii) investigating wideband transmissions for higher throughputs hence new applications [6]. Nevertheless, to the best of our knowledge, except few simulation studies [4], no existing work have tried to mathematically model the ALE standards.

In this paper, we develop a Markovian model of the ALE 2G procedure. The proposed model is channel oriented, i.e., observes the system from channel occupation perspective regardless of node status, and supports computing the performance parameters of interest, namely the ALE duration, and the success and failure probabilities of the procedure. Additionally, we exploit the model to assess the gains of proper LQA frequency ranking. In this way, our model enables the analysis of the complex interplay between different ALE parameters and their influence on the system capabilities, and provides a way to help operator plan and dimension HF 2G deployments.

The remainder of the paper is structured as follows. In Section II we describe the ALE 2G system and the assumptions made in order to develop the Markovian model presented in Section III. Our model is validated in Section IV and then used in Section V to provide an example of exploitation for defining a frequency selection strategy. Finally Section VI concludes the paper.

II. System Description

We focus herein on ALE 2G, the most widely used and *de-facto* interoperability standard [1]. Its main advantage stems from its ability to operate while being completely asynchronous. In other words, at time t, a node can be listening or transmitting on any existing channel without any information on the status of the other nodes. More precisely, the source node sends a call request on a channel for a time duration long enough to enable the receiver to scan all available channel during the emitter transmission. Therefore the size of call request frame depends on the number of available channels for communication in the system. If the receiver is able to detect the call (failure can be due to channels conditions at the receiver side), a handshake is undergone that leads to the establishment of the call. If no answer is received for a call request, the sender moves to the next available channel and initiates a call request on this channel (if any).

A. *ALE 2G access mechanism*

We consider a HF network composed of M nodes. These nodes can exploit a set of N channels for communication and reception. In the ALE 2G, a node selects a single channel i corresponding to a frequency f_i, $i \in \{1, ..., N\}$, for transmitting or receiving. In fact, a node can be in one of the four following states:

- **Listening state.** A node that has nothing to transmit and that is not receiving, listens continuously on the N available channels. Listening is done sequentially by sensing a channel for a short period of time before moving to the next band. A station leaves the listening state in two cases. First, if while scanning a particular channel, it detects a transmission corresponding to a call request with its own address as destination, in which case the station moves to the called state. Second, if it receives internally a call request towards another participating node, in which case the station moves to the calling state.
- **Calling state.** When a node needs to initiate a call it enters in the calling state and follows a procedure to identify a channel on which to communicate with the receiver. For that purpose tests all N channels in sequence: first it checks if the channel f_1 is available: it performs a carrier sensing process for a time denoted as T_{LBT} ("LBT" stands for "Listen Before Talk"). If successful this means that channel f_1 is free (on the caller's side) and then it sends a call initiation request message on that channel containing the receiver's address. If the receiver receives the request with its own address, it accepts the request and sends back an acknowledgement. In this case the successful handshake lasts for a time denoted as T_s. If the receiver is busy or if propagation conditions on that channel are bad, the request message is not answered by the caller. The handshake is considered as a failure after a timeout denoted as T_f. The sender then repeats the procedure sequentially on all N channels.
- **Called state.** A node leaves the listening state to the called state after detecting (through sensing) that he is the intended receiver of a sent establishment request frame. A called station then replies to the caller and awaits for the confirmation from the latter as in classical 3-way handshake procedures. In case the 3-way handshake is not completed successfully, the call request is aborted forcing the caller to find another available channel for making its call and pushing the receiver back to the listening state.
- **Linked state.** Following a successful 3-way handshake exchange (i.e., the end of the ALE), both sender and receiver enter the linked state. Nodes remain in this state for the communication duration.

B. *Assumptions on the system*

We make the following three assumptions:

Assumption 1: A node already in communication cannot respond to a call request coming from another node. Since nodes are equipped with a single transceiver a station in the called state, calling state or linked state, is unable to detect another transmissions addressed to it. These call requests are therefore rejected.

Assumption 2: A new call request arriving locally on a node that is already communicating is lost. We do not consider buffering of incoming calls.

Assumption 3: The "Listen Before Talk" time T_{LBT} is neglected. Because it has a small value with regards to other times involved in the ALE process, we consider that the "Listen Before Talk" time, T_{LBT}, is negligible.

III. Detailed Model

A. *State description*

The model we propose is "channel oriented". This means that it describes the evolution of the state of the N channels without structurally including the state of the M nodes ("listening", "calling", "called" and "linked"). The considered state of the system is thus a vector $\vec{n}$ of N components, each one corresponding to a given channel i, $i \in \{0, 1, ..., N\}$, that can be:

- idle: denoted as f_i and meaning that there is currently no communication or call attempt on channel i;
- used for a call attempt: denoted as $\hat{f}_i$ and meaning that there is a node currently trying to establish a communication with another node on channel i (i.e., there is an ongoing 3-way handshake on channel i that has not yet lead to a success or to a failure);
- used for a communication: denoted as $\bar{f}_i$ and meaning that there is an ongoing communication between two nodes on channel i.

From this state description we derive the state diagram illustrated in Figure 1. This figure represents the transitions out of a particular state $(\hat{f}_1, \bar{f}_2, f_3, \bar{f}_4, \hat{f}_5)$ of a system made of $N = 5$ channels. In this state, channel 3 is idle, channels 2 and 4 are occupied by a communication (between two nodes that are not specified), and channels 1 and 5 are used by nodes that are currently making a 3-way handshake on these two frequencies. From this state, different events may occur. First, one of the two ongoing communications may terminate leading to one of the two upper states. Then, a new call attempt may arrive on one idle node, leading to the right state where the new calling node tries to establish a communication on the

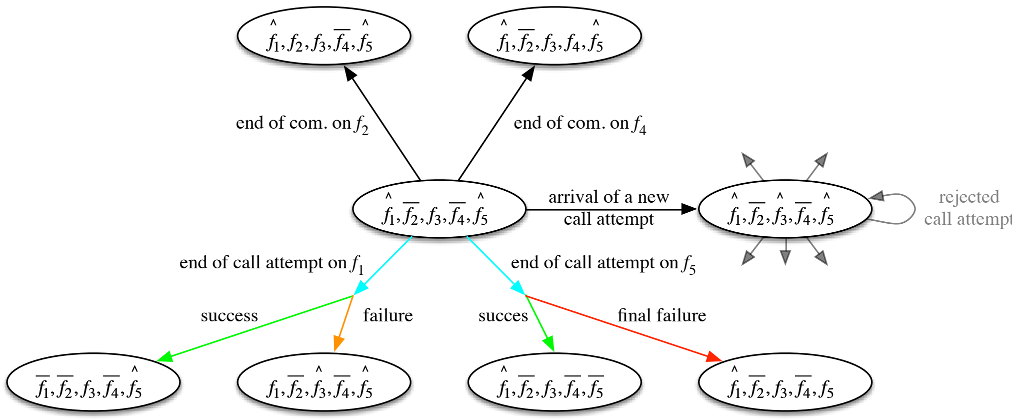

Fig. 1. Channel state diagram

only idle frequency he has found, f_3. Third, the call attempt on frequency f_1 may end because the corresponding 3-way handshake is either a success, leading to the beginning of a new communication on frequency f_1, or a failure, in which case the call attempt is placed on the next idle frequency f_3. Finally, the call attempt on frequency f_5 may end either because the corresponding handshake has been successful, or because the handshake has failed, in which case the call attempt is definitely rejected.

B. Markovian model

In order to transform the above state-description into a Markovian model, we make the following assumptions. First we assume that the arrival process of new call requests on all idle nodes can be globally modeled by a Poisson process with rate λ, and communication times between two nodes can be modeled by exponential distributions of rate μ. These are a very classical assumptions, that we have no reason not to make without any further specifications on the system behavior. Then we assume that a 3-way handshake between a source node and a destination node (on any free channel) has a probability p_s to succeed, resulting in a communication between the two nodes, and a probability $p_f = 1 - p_s$ to fail, forcing the source node to find another free channel to establish the communication. This last assumption can be justified as follows. Two factors are necessary in order for a handshake procedure to succeed. First, the success is related to the good propagation conditions between the nodes (frequency between LUF/MUF, sufficient budget link, no stringent fading...). Second, a success is also conditioned by the fact that the destination node is idle. These two events can reasonably be considered as independent, and the probability of both occurring is thus the product of the probabilities of each of them taken individually. But if the first one can be characterized by a fixed probability, the second one should depend on the load of the system. However, when the number M of communicating nodes is high relative to the number N of frequencies, we can reasonably suppose that this second probability is also constant. Introducing the dependency between p_s and the load will be the focus of future work.

With all these assumptions, the state diagram depicted in Figure 1 can directly be transformed into a Continuous-Time Markov Chain (CTMC) illustrated in Figure 2. The rates of the transitions from state $(\hat{f}_1, \bar{f}_2, f_3, \bar{f}_4, \hat{f}_5)$ to one of the four lower states are the inverse of the average time until a handshake ends (by either a success or a failure), $\frac{1}{p_s T_s + p_f T_f}$, multiplied by the corresponding probabilities p_s or p_f. The upper transitions correspond to the end of a communication (either on f_2 or on f_4) and have thus an associated rate of μ, and the right transition corresponds to a call request arrival (on an idle node) and has thus an associated rate of λ.

C. Performance parameters

The CTMC can be solved using any appropriate numerical technique (such as the Gauss-Seidel technique), that provides the stationary probabilities $p(\vec{n})$ of all states $\vec{n}$ of the chain. We can derive from these probabilities all the performance parameters of interest as follows.

First, we define $ni(\vec{n})$ as the number of idle channels in a given state $\vec{n}$, $nc(\vec{n})$ as the number of channels used for a communication, and $nh(\vec{n})$ as the number of channels used for a handshake. Obviously, for any state $\vec{n}$ of the chain, $ni(\vec{n}) + nc(\vec{n}) + nh(\vec{n}) = N$ at any time.

An arriving call request can eventually result in three events:

1) The call request can be rejected if it arrives when there is currently no idle channel. This is illustrated on Figure 2 for the right state $(\hat{f}_1, \bar{f}_2, \hat{f}_3, \bar{f}_4, \hat{f}_5)$.
2) The call request can eventually result in a success if the source node manage to place a successful handshake on a free channel. This event corresponds to the crossing of a “green transition” in the CTMC illustrated in Figure 2.
3) The call request can eventually result in a failure if the source node does not manage to receive a comprehensible answer from its destination on all tested channels. This event corresponds to the crossing of a “red transition” in the CTMC.

We then define X_r, the average number all call requests rejected by unit of time, X_s the average number of call

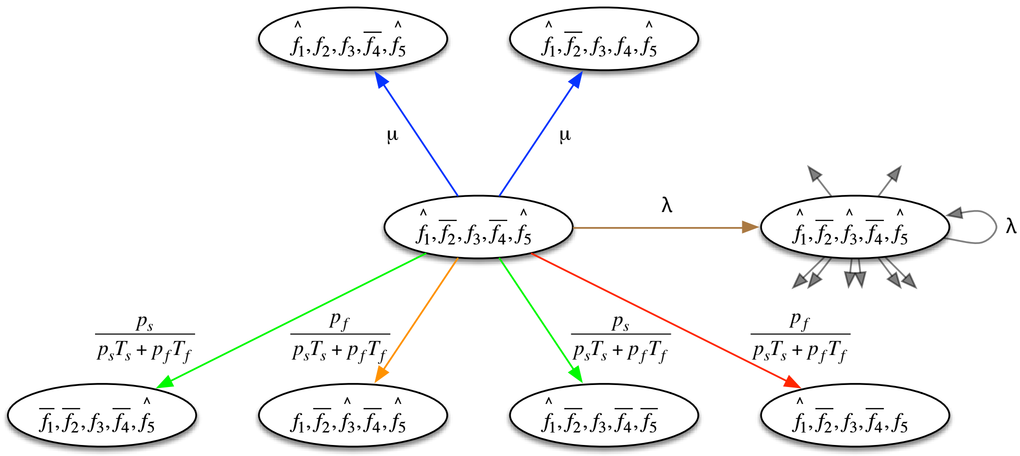

Fig. 2. Markovian model

requests leading to a success (meaning to a communication) by unit of time, and X_f the average number of call requests leading to a failure by unit of time. These throughputs can be estimated as follows. First, X_r is just the number of "loops" crossed by unit of time in the CTMC:

$$X_r = \sum_{\vec{n} \,|\, ni(\vec{n})=0} p(\vec{n})\lambda \tag{1}$$

Then, X_s is the number of crossing of "green transitions" by unit of time:

$$X_s = \sum_{\vec{n}} p(\vec{n}) nh(\vec{n}) \frac{p_s}{p_sT_s + p_fT_f} \tag{2}$$

In order to derive X_f, we first need to define the function $nr(\vec{n})$ as the number of channels used for a handshake in state $\vec{n}$ that are not followed by an idle channel. As an illustration, in state $\vec{n} = (\hat{f}_1, \bar{f}_2, f_3, \bar{f}_4, \hat{f}_5)$, $\hat{f}_1$ is followed by the idle channel f_3, but $\hat{f}_5$ is not followed by any idle channel. As a result, $nr(\hat{f}_1, \bar{f}_2, f_3, \bar{f}_4, \hat{f}_5) = 1$. In fact, $nr(\vec{n})$ corresponds to the number of "red transitions" out of state $\vec{n}$, a red transition corresponding to a "final failure" (see Figure 1). The throughput X_f can now be computed as the number of crossing of "red transitions" by unit of time:

$$X_f = \sum_{\vec{n}} p(\vec{n}) nr(\vec{n}) \frac{p_f}{p_sT_s + p_fT_f} \tag{3}$$

Obviously, the conservation of flows implies that $X_r + X_s + X_f = \lambda$.

From these throughputs, we can now evaluate P_r, the rejection probability of a call request, P_s, the probability that a call request result in a success, and P_f, the probability that a call request result in a failure:

$$P_r = \frac{X_r}{\lambda}, \; P_s = \frac{X_s}{\lambda}, \; P_f = \frac{X_f}{\lambda} \tag{4}$$

In order to calculate another performance parameter of interest, namely the average ALE time, we first calculate Q_h, the mean number of channels used for a handshake:

$$Q_h = \sum_{\vec{n}} p(\vec{n}) nh(\vec{n}) \tag{5}$$

We then derive from Little's law the average duration of an ALE procedure:

$$R_{ALE} = \frac{Q_h}{\lambda} \tag{6}$$

Finally we can calculate the average number of free channels, Q_i, as well as the average number of channels used for a communication, Q_c:

$$Q_i = \sum_{\vec{n}} p(\vec{n}) ni(\vec{n}) \tag{7}$$

$$Q_c = \sum_{\vec{n}} p(\vec{n}) nc(\vec{n}) \tag{8}$$

D. Asymptotic behavior at low load and high load

We develop in this subsection the asymptotic expressions of the performance parameters of interest in the two extreme cases of a very low load and a very high load.

In the case of a very low load, i.e., when λ tends to zero, the rejection probability P_r obviously tends toward 0 and the failure probability P_f tends to ${p_f}^N$. Indeed, when a new call request arrives it has a very high chance to find all N channels idle and the only way for the call request to result in a final failure is to fail on all tested channels. As a consequence, P_s tends toward $1 - {p_f}^N$:

$$P_r^{\lambda\to 0} = 0, \; P_f^{\lambda\to 0} = {p_f}^N, \; P_s^{\lambda\to 0} = 1 - {p_f}^N \tag{9}$$

In order to give the expression of the average ALE duration R_{ALE}, we again use the fact that a call request has a very high chance to find all channels idle upon arrival. Then with a probability ${p_f}^{n-1}p_s$, the call request finally succeeds on frequency f_n, $n = 1, ..., N$, and the ALE duration is $(n-1)T_f + T_s$, and with a probability ${p_f}^N$, the call request finally fails, and the ALE duration is NT_f:

$$R_{ALE}^{\lambda\to 0} = \left(\sum_{n=1}^{N} {p_f}^{n-1} p_s ((n-1)T_f + T_s) \right) + {p_f}^N NT_f \tag{10}$$

The limits in the case of a very high load are obvious:

$$P_r^{\lambda\to\infty} = 1, \; P_f^{\lambda\to\infty} = 0, \; P_s^{\lambda\to\infty} = 0 \tag{11}$$

$$R_{ALE}^{\lambda \to \infty} = 0 \quad (12)$$

IV. Numerical results

In order to validate our Markovian model, we solve numerically the stationary equations associated with the chain via MATLAB (using the Gauss-Seidel technique), and compare the performance metrics to OMNet++ simulations. We apply to simulations the same assumptions as those used for deriving the Markovian model: assumption 1 to 3 as labelled in Section III-A. However, contrarily to the Markovian model which is channel oriented, simulation describes the evolution of the state of each of the M nodes (as detailed in Section II-A), with real transmission over the N available channels.

We consider in our validation a HF system made of $M = 40$ nodes communicating through $N = 5$ channels. An example mean communication time was taken accordingly to typical operational data such as simple text messages (e.g. ACP127 or HF-emails without attachment) that gives $1/\mu = 13.3$ s, and based on the 2G standard, $T_s = 24$ s and $T_f = 21$ s. To respect Assumption 3, we neglect in our simulations the LBT duration ($T_{LBT} = 0$ s). Performance parameters are computed with a varying load λ in the interval $[0; 1]$ call demands per second. Simulations have a variable length, according to λ, in order to get sufficient data for computing performance parameters.

A. Channels occupancy and acceptance rate

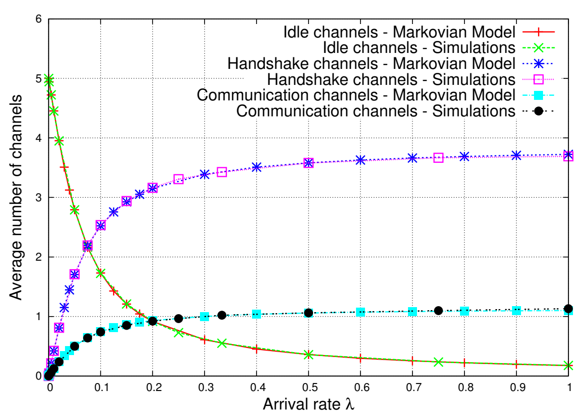

Fig. 3. State of channels in function of the load, for $p_s = 0.5$

Figure 3 shows the occupancy of channels as a function of the load when the success probability $p_s = 0.5$. Recall here that a channel can be in one of the three possible states: idle, in handshake or in communication. The figure compares the average number of channels in each state, Q_i, Q_h and Q_c, derived for the Markovian model (relations 7, 5 and 8), to those obtained from simulation. From this figure one can first observe that our Markovian model matches very accurately the simulations. More precisely, the average relative error between model and simulation is less than 1%, with a maximum error around 3%. Moreover, one can easily notice that the number of idle channels drops quickly with the load. Most importantly, most of the busy channels are occupied by handshake procedures while few of them are used for communications. This suboptimal use of available channels highlights the need for more efficient handshake mechanisms in the coming versions of ALE standards. Figure 3 also shows quite intuitively that the higher the value of λ the more difficult the success of an ALE on a free channel. Besides, we have conducted the same comparisons for different values of success probability p_s and obtained very similar results.

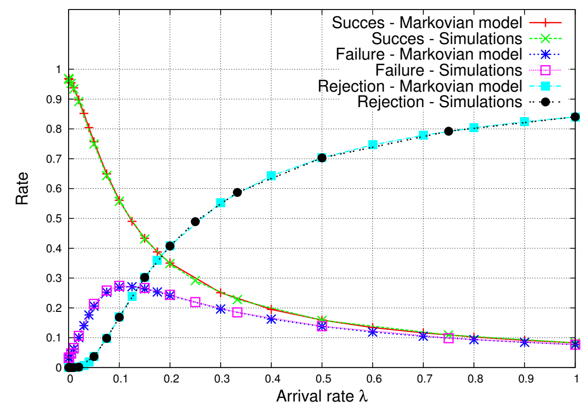

Fig. 4. ALE acceptance rate in function of the load, for $p_s = 0.5$

Figure 4 compares the probabilities of rejection, success and failure, respectively P_r, P_s and P_f, obtained by the model (equation (4)) and by simulations, for $p_s = 0.5$. When load increases, we can see that the failure rate first increases up to a maximum, then decreases toward zero. In the first phase, the increase of λ implies an increase of the number of calls, so more failures occur. Nevertheless, the more λ grows the more channels are occupied, that translates into a raise of the rejection rate and consequently a decrease of the failure rate. Besides, the success (resp. rejection) rates decrease (resp. increase) with the overall system load. Note that these results are corroborated by the asymptotic behavior developed in Section III-D for the rejection probability: $P_r^{\lambda \to 0} = 0$ and $P_r^{\lambda \to \infty} = 1$; for the failure probability: $P_f^{\lambda \to 0} = 0.5^5 = 0.03125$ and $P_f^{\lambda \to \infty} = 0$; and for the success probability: $P_s^{\lambda \to 0} = 1 - 0.5^5 = 0.96875$ and $P_s^{\lambda \to \infty} = 0$.

B. ALE duration

We investigate here the average ALE duration, R_{ALE}. This value is derived from the Markovian model (equation (6)) and compared to simulations. R_{ALE} is depicted in Figure 5 that shows that, in average, the duration of an ALE procedure decreases with λ. In fact, the more λ grows, the less channels are available, therefore fewer channels are tested; at high load, no more channels are available and, as the LBT time is neglected, the call is immediately rejected, thus R_{ALE} decreases towards 0s. Two main observations can be made here. First, these curves confirm again the accuracy of our Markovian model compared to simulations with less than 10% maximum relative errors. Second, also encouraging, the coherence of the limiting values in Figure 5 with the asymptotic behavior computed in Section III-D, where $R_{ALE}^{\lambda \to 0} = 43.594$s and $R_{ALE}^{\lambda \to \infty} = 0$s.

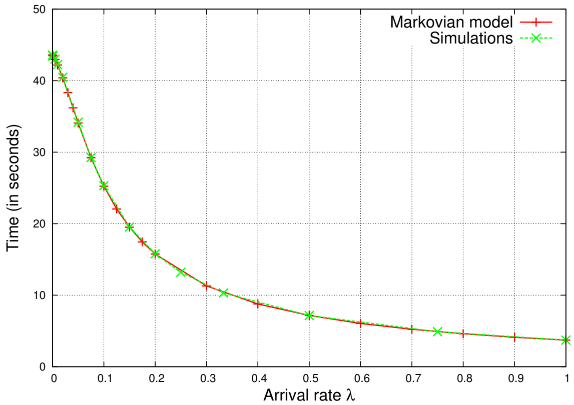

Fig. 5. ALE duration in function of the load, for $p_s = 0.5$

V. Model Exploitation

In this section we illustrate how we can benefit from the capacity of our model to quickly compute the performance parameters of the ALE procedure, in order to investigate the role of ALE parameters and their interplay. Here we examine the influence of the selecting strategies of channels. To do so, we have first extended our model to account for different success probabilities p_s of the different channels. The extension is straightforward and consists only in indexing p_s and p_f with channel numbers and using appropriate values in the Markov chain. We consider a system made of $N = 5$ channels, with a success probability vector $\vec{p_s} = (0.1, 0.3, 0.5, 0.7, 0.9)$.

We compare three possible techniques in selecting channels in the ALE process: "increasing order" refers to the case where the channels are chosen in increasing order of the success probability, i.e., worst first, "decreasing order" refers to the case where the best channel is selected first and the worst last, and finally the "random order" selects channels randomly without considering their success probability.

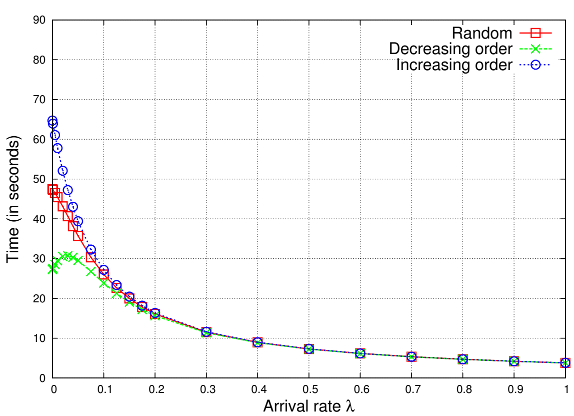

Fig. 6. ALE duration in function of the load, for different frequency selection strategies

In Figure 6, we compare the ALE duration for these three selection strategies. From these curves, two main conclusions can be made. First, at low loads (large sparse networks), selecting first the best available channels for transmissions can drastically reduce the ALE handshake duration. This observation is particularly true when comparing to the increasing order (the worst first) however the gap is lower when compared to a random channel selection strategy. Second, at high loads all selection strategies perform quite similarly in terms of link establishment duration. Indeed, when the load is high, few channels are available and all strategies have approximately the same chance of finding a free channel for transmission. As a result all strategies lead to a comparable ALE duration.

Note that we have also investigated with our model the ALE success probabilities for these three selection strategies. Unsurprisingly, the frequency selection impact is negligible when considering the success rate of the ALE. In other words, a clever channel choice can sometimes make the process faster but its impact on the ALE outcome remains very limited. We do not show these results here for reasons of space limitation.

VI. Conclusion and Future Work

Since late 90's, two standards for HF communications have been proposed. However, in order to prepare the new generation of HF standards capable to take advantage of recent advances in wireless communication and networking, thorough understanding of existing standards and their limitations deems necessary. In this paper we have modeled the HF 2G ALE as a Continuous-Time Markov Chain. We have compared its results to OMNet++ simulations and shown its high accuracy. Our model allows us to set guidelines for designing the next generation of ALE standards. In particular, the handshake duration should be reduced in order to make more channels available for communication. Besides, our model enables the analysis of the complex interplay between different ALE parameters and their influence on the system capabilities. Thus can also serve to plan and dimension ALE 2G networks. In the future, we plan to enrich our model by incorporating the complex link between some input parameters of the model (e.g., p_s) and the load of the system, and relaxing some modeling assumptions (e.g., negligible LBT). Adapting our model to ALE 3G is also an ongoing work.

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