Modélisation d'un mécanisme de prise de ligne dans les réseaux de communication HF

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Bruno Baynat[1], Romain Prouvez[2], Hicham Khalifé[2], Vania Conan[2], and Catherine Lamy-Bergot[2]

[1] *UPMC, France*
[2] *Thales Communications & security, France*

Nous proposons dans ce papier une modélisation par chaîne de Markov d'un mécanisme de prise de ligne (établissement de connexion) dans les réseaux radios HF. Notre approche constitue une première dans ce domaine ou plusieurs générations de mécanismes de prise de ligne ont été proposées depuis la fin des années 90. En effet, avant de concevoir une nouvelle solution capable d'exploiter les avancées notables dans le domaine des communications sans fil, modéliser finement le système et caractériser les interactions entre ses nombreux paramètres s'avèrent nécessaires. En l'occurrence, notre modèle souligne l'impact important de la durée de prise de ligne sur les performances du système. Clairement, les capacités des nouvelles générations d'équipements radios à opérer sur des bandes plus large à la volée doivent être exploitées pour réduire les durées de prise de ligne dans les réseaux HF.

Keywords: MAC multi-fréquences, modélisation, chaînes de Markov

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1 Introduction

HF radio communications provide mostly voice or low-rate data communications with none or minimal infrastructure over very long (up to 10000 km) distance. Because transmissions over such low frequencies are highly dependent on propagation conditions and variations, previous efforts focused on overcoming the extreme variability of the HF ionospheric propagation channel. The main aim was long time concentrating on proposing robust waveforms and physical channels. However, the key feature and challenge of an HF system remain the link establishment procedure. Automatic Link Establishment (ALE) in HF radios allows channel selection between a sender and a receiver dynamically from a pool of existing channels.

Two generations of ALE standards, MIL-STD-188-141 [Sta99] denoted as the ALE 2G, and more recently the STANAG 4538 [NAT00], were already proposed. While several comparisons between these two standards exist today in the literature [TGT12] [KCPM12], to the best of our knowledge, no existing initiative has tried to mathematically model the ALE standards. Therefore, before proposing enhancements or new ALE techniques, a comprehensive modeling of the system and its different parameters can be seen as an important contribution to the community.

In this paper, we model the ALE 2G procedure as a Continuous Time Markov Chain (CMTC). The model we propose is channel oriented, i.e., observes the system from channel occupation perspective regardless of node status. This enables it to scale to systems with large number of nodes. Our Markovian model allows to compute all performance parameters of interest for the ALE 2G. Indeed, this work allows to investigate the network performance for different traffic loads, number of channels, and communication durations.

2 System Description

We focus herein on the MIL-STD-188-141 [Sta99] standard also called ALE 2G. The main advantage of the ALE 2G stems from its ability to operate while being completely asynchronous. In contrast, the ALE 3G requires strict synchronization between all stations. In other words, at time t, a 2G node can be listening or transmitting on any existing channel without any information on other nodes status. In practice, 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 that lasts for the same time duration.

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 mid-band frequency f_i, $i \in \{1,...,N\}$, for transmitting or receiving. In practice, an idle node that wants to establish a new communication with a destination node, first listens to channel 1 during a time T_{LBT}. If it senses a communication (of any kind) on the corresponding frequency band, it moves to channel 2, and so on, until it finds a free channel (if the N channels are busy, the call request is dropped). The source node then starts a 3-way handshake procedure by sending an establishment request frame on the found free channel. If it receives a positive answer from the destination node, the communication between the two nodes starts on the chosen channel. The whole handshake on this channel lasts for a time T_s. If the source node receives no comprehensible answer from the destination node, it considers the handshake as a failure after a timeout T_f. It then tries to establish the communication on another frequency, by sensing the remaining channels one by one. Note that a node can manage only one communication at a time.

3 Model

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. The considered state of the system is a vector $\vec{n}$ of N components, each one corresponding to a given channel i, $i \in \{1,...,N\}$, and in which each component can take three values: 1) idle: denoted as f_i and meaning that there is currently no communication or call attempt on channel i; 2) 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 shall lead to a success or to a failure); 3) 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 on the left of Figure 1 that 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, and channels 1 and 5 are used by nodes that are currently making a 3-way handshake. From this state, different events may occur. First, one of the two ongoing communications may terminate leading to one of the two upper states, $(\hat{f}_1, f_2, f_3, \bar{f}_4, \hat{f}_5)$ or $(\hat{f}_1, \bar{f}_2, f_3, f_4, \hat{f}_5)$. Then, a new call attempt may arrive on one idle node, leading to state $(\hat{f}_1, \bar{f}_2, \hat{f}_3, \bar{f}_4, \hat{f}_5)$ where the new calling node tries to establish a communication on the only idle frequency he has found, f_3. Third, the call attempt on frequency f_1 may end either because the corresponding 3-way handshake has lead to a success, in which case a new communication begins on frequency f_1, leading to state $(\bar{f}_1, \bar{f}_2, f_3, \bar{f}_4, \hat{f}_5)$, or because the handshake has failed, in which case the call attempt is placed on the next idle frequency, f_3, leading to state $(f_1, \bar{f}_2, \hat{f}_3, \bar{f}_4, \hat{f}_5)$. Finally, the call attempt on frequency f_5 may end either because the corresponding handshake has been successful, leading to state $(\hat{f}_1, \bar{f}_2, f_3, \bar{f}_4, \bar{f}_5)$, or because the handshake has failed, in which case the call attempt is definitely rejected, leading to state $(f_1, \bar{f}_2, \hat{f}_3, \bar{f}_4, f_5)$.

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 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. It is worthwhile noting that the success is conditioned by the fact that the destination node is idle and as a result the success probability should actually depend on

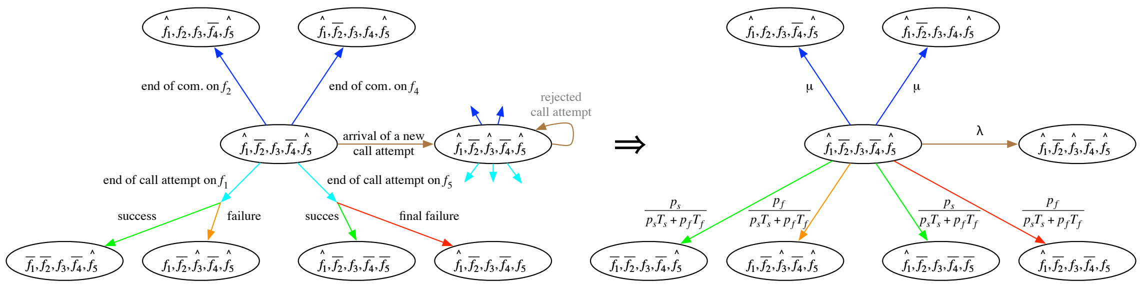


Fig. 1: From state diagram to Markov chain

the load. Taking into account this dependency is actually the focus of future work. With these assumptions, we obtain the Continuous-Time Markov Chain illustrated on the right of Figure 1. 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 include the inverse of the average time until a handshake ends (by either a success or a failure), $\frac{1}{p_sT_s+p_fT_f}$, multiplied by the corresponding probabilities p_s or p_f. The upper transitions correspond to the end of a communication and have thus an associated rate μ, and the right transition corresponds to a call request arrival and has thus an associated rate λ.

We can derive from the stationary probabilities $p(\vec{n})$ of the states of the chain, 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. As an example, for $\vec{n} = (\hat{f}_1, \bar{f}_2, f_3, \bar{f}_4, \hat{f}_5)$, we have $ni(\vec{n}) = 1$, $nc(\vec{n}) = 2$ and $nh(\vec{n}) = 2$. We also need to define $nr(\vec{n})$ 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. Therefore, $nr(\hat{f}_1, \bar{f}_2, f_3, \bar{f}_4, \hat{f}_5) = 1$. 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" as illustrated in Figure 1.

Based on these definitions, 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. We define X_r, the average number all call requests rejected by unit of time. X_r can thus be estimated as follows:

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

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 corresponding to the crossing of a "green transition". The average number X_s of call requests leading to a success by unit of time can thus be expressed as:

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

3. Similarly, the average number of call requests leading to a failure by unit of time, X_f, is then:

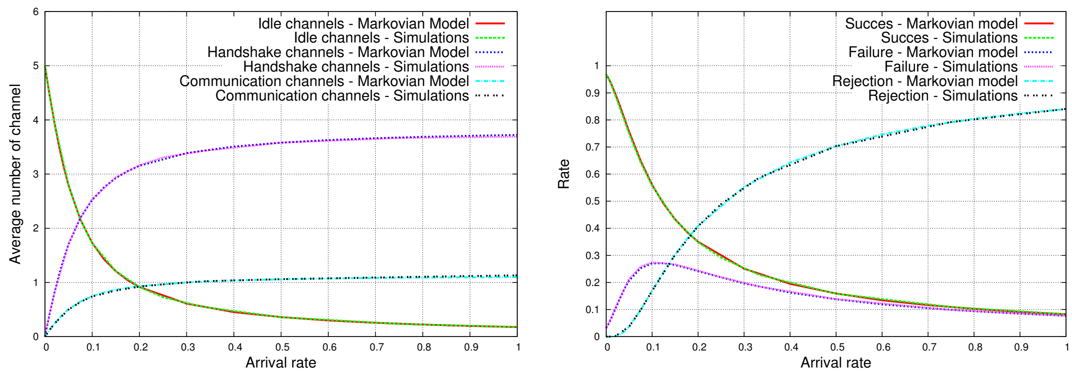
$$X_f = \sum_{\vec{n}} p(\vec{n}) nr(\vec{n}) \frac{p_f}{p_sT_s + p_fT_f} \tag{3}$$

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 results in a failure, as: $P_r = \frac{X_r}{\lambda}$, $P_s = \frac{X_s}{\lambda}$ and $P_f = \frac{X_f}{\lambda}$.

4 Numerical results

In order to validate our Markovian model we solve it numerically via MALTAB and compare the performance metrics to OMNet++ simulations. We have considered in our validation a HF system of $N = 5$

channels, with a success probability p_s of 0.5 and a mean communication time $1/\mu = 13.3$ s. Based on the 2G standard, we assumed $T_s = 24$ s and $T_f = 21$ s, but neglected the LBT duration ($T_{LBT} = 0$ s).



(a) State of channels function of the arrival rate λ

(b) ALE acceptance function of the arrival rate λ

Fig. 2: Channels states and ALE acceptance ratio

Figure 2(a) shows the occupancy of channels (average number of channels that are idle, used for a handshake or used for a communication) as a function of the load. First, one can observe that our Markovian model matches very accurately the simulations. Second, 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 highlights the need for more efficient handshake mechanisms in the coming versions of ALE standards. Now looking at Figure 2(b), 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 a raise of the number of calls, so more failures occur. Nevertheless, the more λ grows the more channels are occupied, that implies a raise of the rejection rate and consequently a decrease of the failure rate. Besides, the sucess (resp. rejection) rates decrease (resp. increase) with the overall system load.

5 Conclusion

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, thourough 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 accuracy. More generally, our model enables the analysis of the complex interplay between different ALE parameters and their influence on the system capabilities.

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