A General Characterization of Sync Word for Asynchronous Communication

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Abstract—We study a problem of sequential frame synchronization for a frame transmitted uniformly in $A$ slots. For a discrete memoryless channel (DMC), Venkat Chandar et al. showed in [1] that the frame length $N$ must scale with $A$ as $e^{N\alpha(Q)} > A$ for the frame synchronization error to go to zero (asymptotically with $A$). Here, $Q$ denotes the transition probabilities of the DMC and $\alpha(Q)$, defined as the synchronization threshold, characterizes the scaling needed of $N$ for asymptotic error free frame synchronization. We show that the asynchronous communication framework permits a natural tradeoff between the sync frame length $N$ and the channel (usually parameterised by the input). For an AWGN channel, we study this tradeoff between the sync frame length $N$ and the input symbol power $P$ and characterise the scaling needed of the sync frame energy $E = NP$ for optimal frame synchronization.

I. INTRODUCTION

Frame synchronization generally concerns the problem of identifying the sync word imbedded in a continuous stream of data (see e.g., [2]). The problem of detecting and decoding frames transmitted sporadically, possibly due to low information rate, is a subject of asynchronous communication. The objective of an asynchronous communication system could be, for example, to detect and decode a single frame transmitted at some random time and there may be no transmission before or after the frame (see e.g., [3]).

The asynchronous communication setup has been discussed in earlier works such as [2] and [4], but the interest has increased in recent times with emerging applications in wireless sensor networks and the Internet of Things (IoT). In wireless sensor and actor networks (see e.g., [5] and [6]), the participating nodes would report a measurement or an event to the fusion centre at random epochs. The nodes may need to transmit few bytes of data to the fusion centre over a relatively large time frame, e.g., a single packet possibly in an hour or even in a day. Also, in frameworks such as IoT [7], the nodes may report measurements sporadically leading to an asynchronous communication framework. However, the constraints on power may be less stringent in IoT than in wireless sensor networks. Characterisation of the communication overheads (e.g., synchronisation overheads) needed in such set-ups is crucial for optimal network design and operation.

Related Literature: Earlier works on frame synchronization, such as [2] and [8], used the maximum-likelihood (ML) criteria for periodically occurring sync words. For aperiodic sync words, hypothesis testing (sequential frame sync) was preferred in works such as [9], [10] and [11]. For the asynchronous set-up (one-shot frame sync), both ML criteria (e.g., [4]) and hypothesis testing (e.g., [12] and [13]) have been studied. These works focus only on the design and performance of receivers for a sync word designed independently.

For the asynchronous set-up, Chandar et al. [1] characterized the optimum system performance considering sync word and receiver design jointly. They study a problem of sequential frame synchronization for a frame transmitted randomly and uniformly in an interval of known size. For a discrete memory-less channel, they identified a synchronisation threshold that characterises the sync frame length needed for asymptotic error-free frame synchronisation. In [3], following [1], a framework for communication in an asynchronous set up was proposed and achievable trade-off between reliable communication and asynchronism was discussed. In our work, we restrict to frame synchronization but generalise the framework presented in [1] to study a tradeoff between the sync frame length and the channel. For the AWGN channel, this tradeoff permits us to characterise the scaling needed of the sync frame energy (instead of the sync frame length considered in [1] and [3]) for optimal frame synchronisation.

II. SYSTEM SET-UP

The problem set-up is illustrated in Figure 1. We consider discrete-time communication between a transmitter and a receiver over a discrete memory-less channel. The discrete memory-less channel is characterized by finite input and output alphabet sets $X$ and $Y$ respectively, and transition probabilities $Q(y|x)$ defined for all $x \in X$ and $y \in Y$.

A sync packet $s^N = (s_1, \ldots, s_N)$ of length $N$ symbols ($s_i \in X$ for all $i = 1, \ldots, N$) is transmitted at some random time, $v$, distributed uniformly in $\{1, 2, \ldots, A\}$, where $A$ is assumed known. The transmission occupies slots $\{v, v+1, \ldots, v+N-1\}$ as illustrated in Figure 1 i.e., $x_n = s_{n-v+1}$ for $n \in \{v, \ldots, v+N-1\}$, and, we assume that the channel input in slots other than $\{v, v+1, \ldots, v+N-1\}$ is $x(0)$ (where $x(0) \in X$ and could represent zero input). The distribution of the channel output, $\{y_n\}$, conditioned on the random transmission time $v$ and the sync sequence $s^N$, is $Q(\cdot | s^N_{-v+1})$ for $n \in \{v, v+1, \ldots, v+N-1\}$ and $Q(\cdot | x(0))$ otherwise.

The receiver seeks to identify the location of the sync packet $v$ from the channel output $\{y_n\}$. Let $\hat{v}$ be an estimate of $v$. Then, the error event is represented as $\{\hat{v} \neq v\}$ and the associated probability of error in frame synchronization would be $P(\{\hat{v} \neq v\})$. We are interested in characterizing the
Section [V] for the AWGN channel, we discuss the tradeoff between the sync frame length $N$ and the input symbol power $P$ and characterise the scaling needed of the sync frame energy $E = NP$ for error-free frame synchronization.

Chandar et al [1] studied the sequential construction problem for a fixed $Q$ (and $\alpha(Q)$) and as a function of the sync frame length $N$ only. Also, in [1], the setup and the proof based on the joint typicality of input-output sequences requires the sync frame length $N$ to scale to infinity. In our work, we generalise the framework and study a tradeoff between the sync frame length $N$ and channel parameters and study the case of finite sync frame length as well.

IV. A GENERAL FRAMEWORK FOR ASYNCHRONOUS FRAME DETECTION

We now present a framework that permits a tradeoff between the sync frame length $N$ and the channel, represented by $\alpha(Q)$, for the system setup described in Section [II]. Consider a sequence of triples, channel, sync word and sequential decoder, $\{(x_A, y_A, Q_A), s^{N_A}, \tilde{v}\}$ parameterized by the asynchronous interval length $A$. Define $\alpha(Q_A)$ as

$$\alpha(Q_A) = \max_{x \in \mathcal{X}_A} D(Q_A(\cdot|x)||Q_A(\cdot|x_A(0)))$$

and let $x_A(1) := \arg \max_{x \in \mathcal{X}_A} D(Q(\cdot|x)||Q(\cdot|x_A(0)))$. The following theorem generalizes Theorem 1 in [1] and discusses the necessary scaling needed of $N_A$ and $\alpha(Q_A)$ for asymptotic error-free frame synchronisation.

Theorem 1. Consider a sequence of triples, $\{(x_A, y_A, Q_A), s^{N_A}, \tilde{v}\}$ parameterized by the asynchronous interval length $A$. Let $N_A \to \infty$ as $A \to \infty$. Let $Q_A(\cdot|x_A(1)) \to Q^*_1(\cdot)$ and $Q_A(\cdot|x_A(0)) \to Q^*_0(\cdot)$ such that $\alpha(Q_A) \to \infty$ as $A \to \infty$. Then, the probability of frame detection error $P(\{\tilde{v} \neq v\}) \to 0$ as $A \to \infty$ if $e^{N_A\alpha(Q_A)} > A$.

Remarks IV.1.

1) Theorem [1] characterizes the rate at which $N_A$ and $\alpha(Q_A)$ must scale with $A$ for the frame synchronisation error to tend to zero (asymptotically). In [1], the channel was assumed to be the same independent of $N$ or $A$. The generalisation proposed in Theorem [II] enables us to study the tradeoff between $N_A$ and $\alpha(Q_A)$ for supporting asynchronism.

2) For the AWGN channel, we know that $\alpha(Q_A) = \frac{P_A}{2\sigma^2}$. Hence, $N_A \times \alpha(Q_A) \sim N_A P_A$ represents the energy of the sync packet. Thus, the above theorem also characterizes the necessary scaling needed of the energy of the sync packet for the frame synchronisation error to tend to zero. This observation is studied in detail in Section [V] of this paper.

Here, we have presented only the necessary outline of the proof for Theorem [II] as the argument is similar to the presentation in [1].

Proof:

Setup: We consider the framework presented in Section [II] for every $A$. A sync packet $s^{N_A}$ of length $N_A$ is transmitted
at some random time $v \sim U\{1, A\}$. The discrete memory-less channel is characterised by finite input and output alphabet sets $X_A$ and $Y_A$ respectively, and transition probabilities $Q_A(\cdot|\cdot)$ with synchronisation threshold $\alpha(Q_A)$ defined as in (3).

**Codeword:** Following (1), we consider a sync sequence $s^{N_A}$ of length $N_A$ with the following properties.

1. Fix some large $K$. Now, find a $M_A$ such that $2^{M_A-1} - 1 < \frac{A}{\alpha}$ for some $M_A = 1, 2, \ldots$. Let $s_n = x_A(1)$ for $2^{M_A} - 1 < n \leq N_A$. Consider a maximal-length shift register (MLSR) sequence \{m_n : n = 1, 2, \ldots, 2^{M_A} - 1\} of length $2^{M_A} - 1$ and map it to \{s_n : n = 1, 2, \ldots, 2^{M_A} - 1\} such that $s_n = x_A(1)$ if $m_n = 0$ and $s_n = x_A(0)$ if $m_n = 1$.

2. The sync sequence thus obtained, $s^{N_A}$, now has a Hamming distance of $\Omega\left(\frac{N_A}{2^R}\right)$ with any of its shifted sequences.

**Decoder:** We consider a simple version of the sequential joint typicality decoder for the problem setup. In (1), at every time $t + N_A - 1$, the decoder computes the empirical joint distribution $\hat{P}$ of the sync word (the channel input of length $N_A$) and the output symbols in the previous $N_A$ slots, i.e., $\{y_t, \ldots, y_{t-N_A-1}\}$. Whereas, we restrict our attention to those positions in the sync word where we transmit symbol $x_A(1)$ and only compute

$$\hat{P}(x_A(1), y) = \frac{N(x_A(1), y)}{N_A^1}, \text{ for all } y \in Y,$$

where $N_A^1$ denotes the number of occurrences of $x_A(1)$ in the sync word and $N(x_A(1), y)$ denotes the number of joint occurrences of $(x_A(1), y)$ in the sync code word and the channel output. We note that $N_A^1 = \Omega\left(\frac{N_A}{1 - \frac{1}{\mu}}\right)$.

If the empirical distribution is close enough to the expected distribution $Q_A(\cdot|x_A(1))$, i.e., if $|\hat{P}(\cdot) - Q_A(\cdot|x_A(1))| < \mu$ for some fixed $\mu > 0$, then, the decoder declares $\hat{v} = t$. We have assumed that $Q_A(\cdot|x_A(1)) \rightarrow Q_1(\cdot)$ and hence, we make a simplifying assumption and declare $\hat{v} = t$ only when $|\hat{P} - Q_1(\cdot)| < \mu$.

**Error event:** The failure to detect the exact instance of sync word transmission, i.e., the error event $\{\hat{v} \neq v\}$, can be partitioned as given below and as shown in Figure 2.

- $E_1 : \hat{v} \in \{1, \ldots, v - N_A\} \cup \{v + 1, \ldots, A\}$. This corresponds to the event that the output symbols generated entirely by the zero input $x_A(0)$ is jointly typical.
- $E_2 : \hat{v} \in \{v - N_A + 1, \ldots, v - 1\}$. This corresponds to the event that the output symbols generated partially by $x_A(0)$ and sync word is jointly typical.
- $E_3 : \hat{v} \notin \{v\}$. This corresponds to the event that the output symbols generated by the sync word is not jointly typical.

In detection terminology, $E_1$ and $E_2$ both constitute false alarm due to noise emulation of sync word and $E_3$ is missed detection.

**Performance Evaluation:** Using a union bound, we can upper bound the probability of error in frame synchronisation as

$$P(\{\hat{v} \neq v\}) \leq P(E_1) + P(E_2) + P(E_3).$$

Suppose that $A = e^{\epsilon_1 N_A(\alpha(Q_A) - \epsilon_2)}$ for some $0 < \epsilon_1 < 1$ and $\epsilon_2 > 0$, i.e., $A < e^{N_A(\alpha(Q_A))}$. We will now show that $P(E_1), P(E_2)$ and $P(E_3)$ tend to zero as $A \to \infty$.

The proof follows the method of types (see (12) and (13)). A false alarm event of type $E_1$ occurs at a time $t$, if an input sequence composed entirely of $x_A(0)$ symbols generates an output type in the set $Q^* = \{Q(\cdot) : |Q(y) - Q_1(\cdot)| < \mu, \forall y \in Y\}$. The probability of such an event is bounded as

$$P(E_1|t) \leq \sum_{Q \in Q^*} e^{-N_A^1 D(Q(\cdot)||Q_A(\cdot|x_A(0)))} \leq \text{poly}(N_A^1) e^{-N_A^1(\alpha(Q_A) - \delta)}$$

where $\delta$ is a function only of $\mu$ and is independent of $A$. The probability of false alarm of type $E_1$ can now be upper bounded using a union bound (over $t$) as follows.

$$P(E_1) \leq A \times \text{poly}(N_A^1) e^{-N_A^1(\alpha(Q_A) - \delta)}$$

Substituting for $A = e^{\epsilon_1 N_A(\alpha(Q_A) - \epsilon_2)}$ and bounding $N_A^1$, we have

$$P(E_1) \leq \text{poly}(N_A) \times e^{\epsilon_1 N_A(\alpha(Q_A) - \epsilon_2)} \times e^{-N_A(1 - \frac{1}{\mu})(\alpha(Q_A) - \delta)} \tag{4}$$

For large $K$ and small $\delta$ (with an appropriate choice of $\mu$), we have, $P(E_1) \to 0$ as $A \to \infty$ (i.e., as $N_A \to \infty$ or as $\alpha(Q_A) \to \infty$).

A false alarm event of type $E_2$ occurs if an input sequence composed partially of $x_A(0)$ symbols and the sync word $s^{N_A}$ generates an output type in the set $Q^*$. We note that, for every transmission instant $v$, there are $N_A - 1$ possible positions that can lead to the error event. The MLSR sequence achieves a Hamming distance of $\Omega\left(\frac{N_A}{2^R}\right)$ with any of its shifted versions and, the Hamming distance corresponding to positions where the sync word is $x_A(1)$ is $\Omega\left(\frac{N_A}{2^R}\right)$. Using similar arguments as for $E_1$, the probability of false alarm of type $E_2$ can now be upper bounded as

$$P(E_2) \leq \text{poly}(N_A) \times e^{-\Omega\left(\frac{N_A}{2^R}\right)\alpha(\delta)} \tag{5}$$

Here again, $P(E_2) \to 0$ as $A \to \infty$ (i.e., as $N_A \to \infty$ or as $\alpha(Q_A) \to \infty$).
For the missed detection event \( E_A \), we need to evaluate the probability that an input sequence composed entirely of \( x_A(1) \) symbols generates an output type outside the set \( Q^* \). Clearly,

\[
P(E_A) \leq \sum_{Q \notin Q^*} e^{-N_A^2|Q||Q_A(1)|x_A(0)}
\]

\[
\leq \text{poly}(N_A) \times e^{-N_A(1 - \varepsilon')\delta'}
\]  

(6)

where \( \delta' \) is a function only of \( \mu \) and is independent of \( A \). Now, \( P(E_A) \to 0 \) as \( A \to \infty \) (i.e., as \( N_A \to \infty \)). We note that the scaling of \( \alpha(Q_A) \) does not take the error probability \( P(E_A) \to 0 \).

Thus, we have \( P(\{\hat{v} \neq v\}) \to 0 \) if \( N_A \to \infty \) and \( \alpha(Q_A) \to \infty \) such that \( e^{N_A\alpha(Q_A)} > A \).

\[ \blacksquare \]

V. Trade-off in AWGN Channel

In this section, we study the application of Theorem 1 to the additive white Gaussian noise channel. We make the following additional assumptions to define a binary input binary output DMC model for the AWGN channel.

1) We consider a binary input alphabet set \( \mathcal{X}_A = \{x_A(0) = 0, x_A(1) = \sqrt{P_A}\} \) for every \( A \). \( P_A \) could correspond to the symbol power constraint and \( P \) would then be the SNR. We note that it is sufficient to consider the binary input alphabet set for the frame synchronisation problem (see Section II or [1] for details).

2) The received signal at time \( n \) is assumed to be \( x_n + w_n \), where \( w_n \) is WGN with variance \( \sigma^2 \).

3) We consider a binary alphabet set \( \mathcal{Y}_A \) for the output channel, i.e., \( \mathcal{Y}_A = \{y_A(0), y_A(1)\} \) for every \( A \). In particular, we consider the following map for the AWGN channel: the output is \( y_A(1) \) if \( x_n + w_n > \tau_A = a\sqrt{P_A} \) for some \( 0 < a < 1 \) and the output is \( y_A(0) \) if \( x_n + w_n \leq \tau_A \). The binary input and binary output DMC model for the AWGN channel is illustrated in Figure 3 where \( \epsilon_f \) and \( \epsilon_m \) denote the transition probabilities. We show in Section V-A that the two alphabet approximations for the output channel are appropriate in the context of asynchronous frame synchronisation.

A. Binary Output DMC Model for AWGN Channel

The synchronisation threshold for the AWGN channel with noise power \( \sigma^2 \) and input symbol power \( P \) was shown to be \( \frac{P}{2\sigma^2} \) (see [1]). The following lemma shows that the binary input binary output model for the AWGN channel can achieve a synchronisation threshold arbitrarily close to \( \frac{P}{2\sigma^2} \).

Lemma 1. Consider the binary input binary output model for the AWGN channel shown in Figure 3. The synchronisation threshold of the DMC tends to \( \frac{P}{2\sigma^2} \) for \( a \approx 1 \) and as \( P \to \infty \).

Proof: The channel transition probabilities for the DMC are

\[
\epsilon_f = P(y_A(1)|x_A(0)) = P(n > a\sqrt{P}) \approx e^{-\frac{a^2P}{2\sigma^2}}
\]

\[
\epsilon_m = P(y_A(0)|x_A(1)) = P(n > (1 - a)\sqrt{P}) \approx e^{-\frac{(1 - a)^2P}{2\sigma^2}}
\]

Fig. 3. A binary input binary output model for AWGN channel with transition probabilities \( \epsilon_f = P(y_A(1)|x_A(0)) = P(n > a\sqrt{P}) \) and \( \epsilon_m = P(y_A(0)|x_A(1)) = P(n > (1 - a)\sqrt{P}) \).

The synchronisation threshold for the binary DMC is given by

\[
\alpha = (1 - \epsilon_m) \log \frac{1 - \epsilon_m}{\epsilon_f} + \epsilon_m \log \frac{\epsilon_m}{1 - \epsilon_f}
\]

Clearly, \( \epsilon_f, \epsilon_m \to 0 \) as \( P \to \infty \). Hence,

\[
\alpha \to - \log \epsilon_f + \epsilon_m \log \epsilon_m \approx \frac{a^2P}{2\sigma^2} + \frac{(1 - a)^2P}{2\sigma^2} e^{-\frac{(1 - a)^2P}{2\sigma^2}}
\]

\[
\approx \frac{a^2P}{2\sigma^2}
\]

Thus, for large \( P \) and \( a \) close to 1, the synchronisation threshold of the binary input binary output tends to the synchronisation threshold of the AWGN channel.

The above lemma permits us to apply the results of the Section IV for the AWGN channel.

B. Tradeoff for the AWGN Channel

The following corollary discusses an application of Theorem 1 for the AWGN channel.

Corollary 1. Consider an AWGN channel with noise variance \( \sigma^2 \). Let \( N_A \) and \( P_A \) denote the sync word length and the input symbol power parameterized by the asynchronous interval length \( A \). Let \( N_A, P_A \to \infty \) as \( A \to \infty \). Then, the probability of frame detection error \( P(\{\hat{v} \neq v\}) \to 0 \) if \( e^{N_A P_A \frac{1}{2\sigma^2}} > A \).

Proof: We know that \( \alpha(Q_A) \to \frac{a^2 P_A}{2\sigma^2} \approx \frac{P_A}{2\sigma^2} \) for the binary input binary output model for the AWGN channel as \( P_A \to \infty \). Also, as \( P_A \to \infty \), we see that \( Q_A(|x_A(1)) \to (0, 1) \) and \( Q_A(|x_A(0)) \to (1, 0) \) satisfying the assumptions. Hence, \( e^{N_A \alpha(Q_A)} \to e^{N_A \frac{P_A}{2\sigma^2}} \) as \( A \to \infty \). From Theorem 1 we then have \( P(\{\hat{v} \neq v\}) \to 0 \) as \( A \to \infty \) if \( e^{N_A \frac{P_A}{2\sigma^2}} > A \).

Remarks V.1.

1) Define \( E_A = N_A P_A \) as the energy of the sync packet. Then, the above corollary characterises the scaling necessary of the energy of the sync packet (when both \( N_A \) and \( P_A \) are adapted) for asymptotic error-free frame synchronisation.

The following lemma extends the results of Corollary 1 for a sync word of finite length.
Lemma 2. Consider an AWGN channel with noise variance \( \sigma^2 \). Let \( N_A \) and \( P_A \) denote the sync word length and the input symbol power parameterised by the asynchronous interval length \( A \). Let \( N_A = N \) for all \( A \) and let \( P_A \rightarrow \infty \) as \( A \rightarrow \infty \). Then, the probability of frame detection error \( P(\{ \hat{v} \neq v \}) \rightarrow 0 \) if \( e^{N P_A \frac{\sigma^2}{2}} > A \).

Proof: The proof follows similar arguments as in Theorem \( \Box \). Here again, we seek to show that \( P(\{ \hat{v} \neq v \}) \leq P(E_1) + P(E_2) + P(E_3) \rightarrow 0 \) under the suggested conditions.

Codeword: Since \( N \) is finite, we will simplify the sync word and let it consist only of \( x_A(1) = \sqrt{\frac{A}{n}} \) in all the positions.

Decoder: As the sync word comprises only of \( x_A(1) \), the entire length of the sync word is used for decoding. As \( P_A \rightarrow \infty \), we see that \( Q_A(|x_A(1)|) \rightarrow (0, 1) = Q_1^* \). The decoder will declare \( \hat{v} = t \) if \( |P - Q_1^*| < \mu \). For the finite \( N \) case, we will set \( \mu = \frac{1}{N} \). Then, for the choice of \( \mu \), we have \( Q^* = \{Q(\cdot): |Q(y) - Q_1(y)| \leq \frac{\mu}{4}, \forall y = \{0, 1\} \} \). This implies that the decoder will declare the sync packet as received only when all the previous \( N \) output symbols are decoded as \( y_A(1) \).

Performance Evaluation: The probability of false alarm of type \( E_1 \) for the decoder can now be upper bounded as

\[
P(E_1) \leq A \times e^{-N \frac{P_A}{2} \sigma^2} \leq A \times e^{-N \frac{P_A}{2} \sigma^2}
\]

If \( A = e^{N \frac{P_A}{2} \sigma^2} < e^{N \frac{P_A}{2} \sigma^2} \) for some \( 0 < \epsilon < 1 \), then we have \( P(E_1) \rightarrow 0 \) as \( P_A \rightarrow \infty \) for a suitable choice of \( a \).

The probability of false alarm of type \( E_2 \) can be upper bounded by considering the worst case overlap with the sync word and using a union bound as given below.

\[
P(E_2) \leq (N - 1) e_{\epsilon^f} \leq (N - 1) e^{-N \frac{P_A}{2} \sigma^2}
\]

Clearly, \( P(E_2) \rightarrow 0 \) as \( P_A \rightarrow \infty \).

The missed detection occurs even if one of the symbols is in error, since \( \mu = \frac{1}{N} \). Thus, using a union bound, the probability of missed detection is upper bounded as

\[
P(E_3) \leq N e_{\epsilon m} \leq N e^{(1 - \frac{N^2 P_A}{2} \sigma^2)}
\]

\( P(E_3) \rightarrow 0 \) as \( P_A \rightarrow \infty \). Hence, \( P(\{ \hat{v} \neq v \}) \rightarrow 0 \) as \( P_A \rightarrow \infty \).

VI. Conclusion

In this paper, we present a general framework for asynchronous frame synchronisation which permits a trade-off between sync word length \( N \) and channel. The framework allowed us to characterise the synchronisation threshold for the AWGN channel in terms of the sync frame energy (i.e., \( e^{N \frac{P_A}{2} \sigma^2} > A \)) instead of the sync frame length. We also observe that a finite sync word can achieve optimal frame synchronization for an AWGN channel. As future work, we seek to study this trade-off for wireless channel models.

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