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Randomizer for High Data Rates

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To be presented by Howard Garon and Victor Sank at the Consultative Committee for Space Data Systems (CCSDS)
Spring Technical Meetings, Gaithersburg, MD, April 9-13, 2018.

Background

It has been known for quite a while that the CCSDS randomizer with length of only 255 causes spikes in the RF spectrum. This is of particular interest in high data rate telemetry but as command rates go higher, it may also become an issue there.

Several space agencies and commercial entities have been aware of this problem and there have been previous CCSDS presentations (2006 - 2008) related to the need for a longer CCSDS randomizer. These documents, (among others) can be found by entering “randomizer” in the CCSDS CWE far right “Search this site”.

Additional references shown at end of presentation.

[1] ESA.Polito.HDRandomizer.BERLIN10.pdf, Oct 2008.
[2] randomizer_slides_esoc_polito_univpm.pdf, Apr 2009.
[3] randomizer_report_esoc_polito_univpm.pdf, Apr 2009.
[4] Initial Study. ESA.Polito.Randomizer.Garello.USA5.pdf, Mar 2008.

Under ESA sponsor, the Politecnico di Torino and the Università Politecnica delle Marche, a linear feedback shift register (LFSR) of length 32,767, was recommended,

$$h(X) = X^{15} + X^{14} + 1$$

Background

The current CCSDS TLM randomizer is a PN 8 which has a length of $L = 2^8 - 1 = 255$ symbols.

CCSDS 131.0-B-3, 10.4.1 The pseudo-random sequence shall be generated using the following polynomial: $h(x) = x^8 + x^7 + x^5 + x^3 + 1$

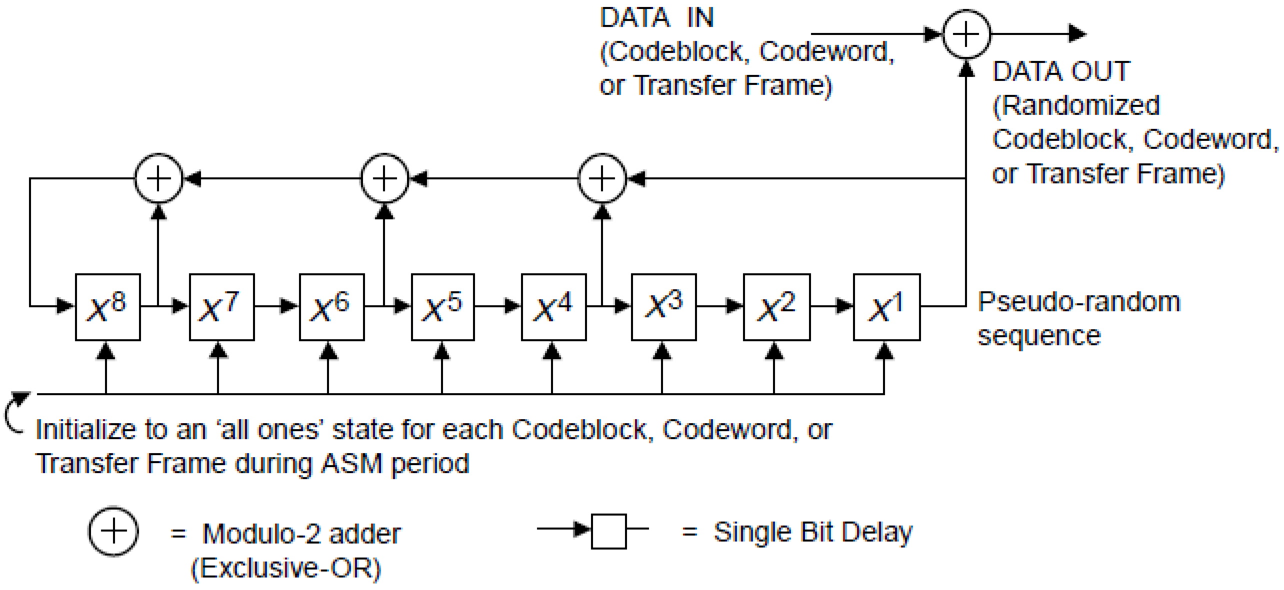
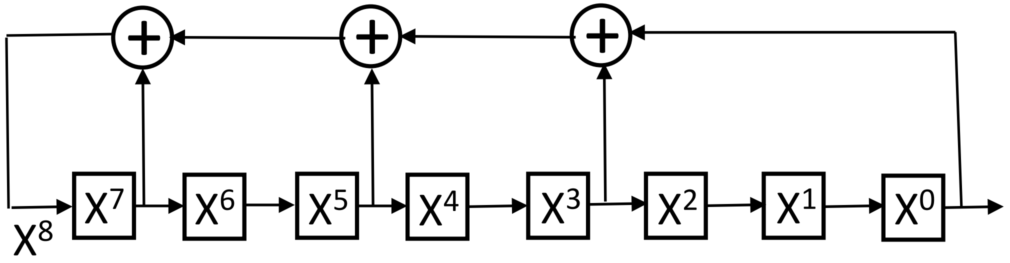


Figure 10-2: Pseudo-Randomizer Logic Diagram

Polynomial defines the pattern but without diagram or definition of cell numbering, the direction of flow is ambiguous.

CCSDS is inconsistent with the cell numbering. In this paper we use the cell numbering with 1 as the input and M the output to be consistent with previous papers (slides 16 and 22). However, we note that other numbering of the cells more naturally makes an association with the polynomial



Initialization not shown.
The taps here are at cells 8, 7, 5, 3, and 0
Which lead to a polynomial of
$X^8 + x^7 + x^5 + x^3 + x^0 = X^8 + x^7 + x^5 + x^3 + 1$

Background

The current CCSDS TLM randomizer is a PN8 which has a length of $L = 2^8 - 1 = 255$ symbols.

At a coded data rate of 100 Mcsps (Mega code symbols per second) with (O)QPSK modulation, there will be 50 Mmsps (Mega modulation symbols per second). A detail is that the OQPSK which staggers the data on the I and Q channels, will have the same PN 8 on each channel. So the repeat rate is

$$(100 \text{ Msps}/2)/255 = 196078.4 \text{ per second} = 196 \text{ KHz}.$$

This will show up on a spectrum as a spike every 196 KHz.

The problem will be particularly observable with CADUs that are only idle data (OID) but will exhibit itself on other CADUs also.

Rs = coded symbol rate
m = modulation order ($m_{BPSK} = 1$, $m_{QPSK} = 2$, …)
L = Randomizer pattern length

For modulation orders where m is a power of 2, the rate of spikes is

$$f_{spike} = (Rs/m)/L$$

Background

Randomness is required to mitigate several problems:

- Bit / Code-symbol synchronization
- Signal acquisition when not using sweep of a CW signal
- Code synchronization ambiguity
- Spectrum spikes that violate regulations (Power Spectral Density problems)

ITU Recommendation [1]:

1. **Spurious must be separated at maximum by 4 kHz**
2. **Spurious amplitudes less than 6 dB over ideal PSD**

To meet **1.**, $Rs_{max} = m\ L\ f_{spike\ max} = 2 \times 255 \times 4\ \text{KHz} = 2.0\ \text{Msps}$

Current randomizer
Single data channel OQPSK

Current randomizer satisfies requirement only up to 2.0 Msps

For PN15, L = 32,767 and Rs = 262 Msps and for PN17, L = 131,071 and Rs = 1.05 Gsps

Considerations for a new Randomizer

- Must be random over both short and long transfer frames and code blocks.
- May or may not start at all ones epoch.
- PN 14, 15, 16, 17 (= M) will cover most maximum length frames or code blocks.
- Patterns are good for [m L $f_{\text{spike max}}$ = 131, 262, 524], 1048 Msps respectively
  using m = 2, $L = 2^M - 1$, $f_{\text{spike max}}$ = 4 KHz.
- A minimum number of taps is desired, for easy pattern generation.
- Since randomizer restarts at each code block when randomizer is longer than code block, Spurious rate depends on code block length, not randomizer length.

Considerations for a new Randomizer

Transfer Frame Length vs Randomizer Length

For uncoded and convolutionally coded TFs, randomization is done at the transfer frame (TF) level and the length is limited to 2048 octets = 16384 bits (CCSDS 131.0-B-3).

The maximum length of the TF depends on the coding option chosen.

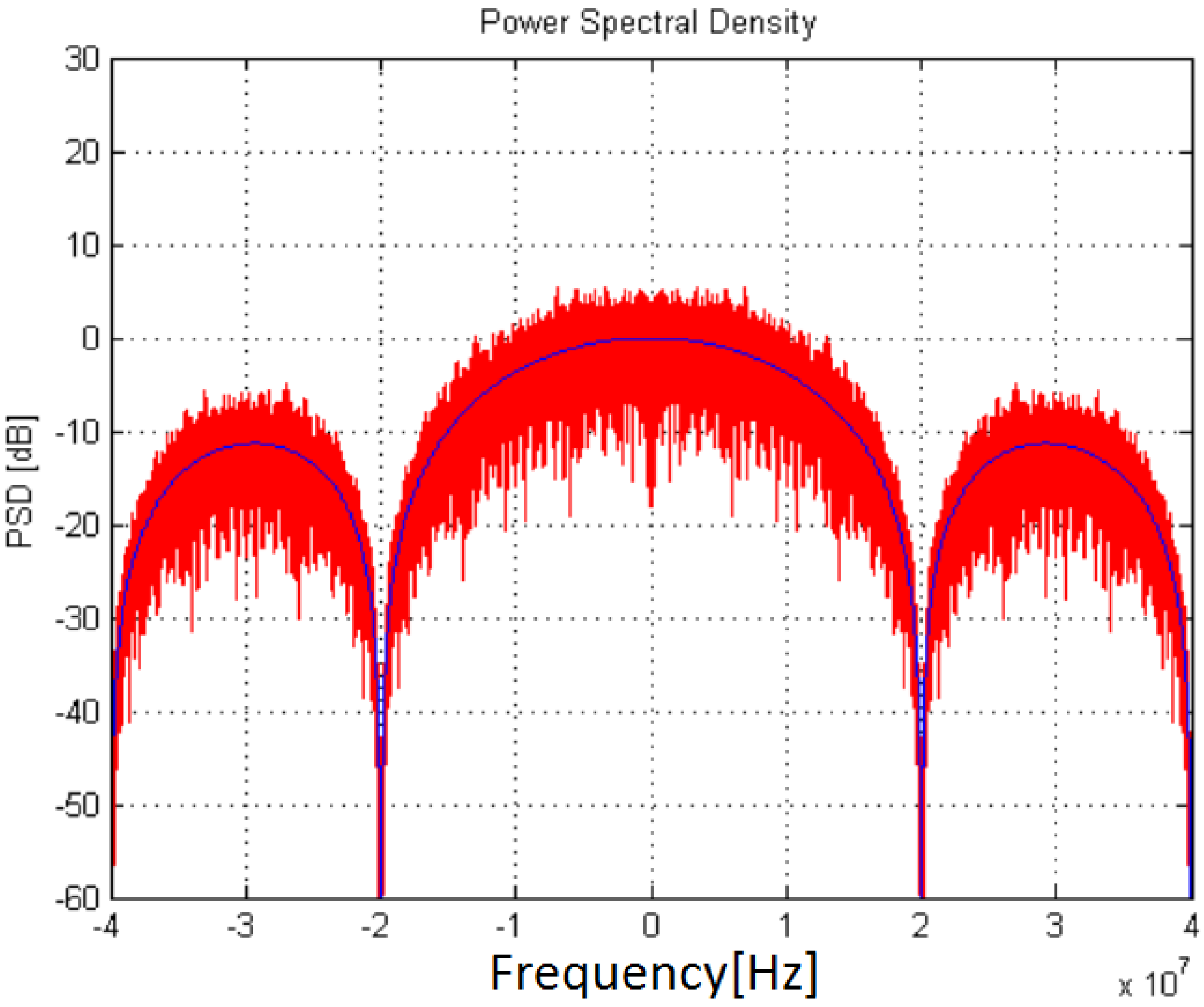
When block coded, randomization is done at the level of the block code, the CADU. The code block synchronization marker (ASM or CSM) is not randomized.

Considerations for a new Randomizer

From [1] with PN15, $X^{15} + X^{14} + 1$

ITU Recommendation [1]:

1. Spurious must be separated at maximum by 4 kHz
2. Spurious amplitudes less than 6 dB over ideal PSD



For Rs = 40 Msps
OQPSK
CADU length for RS with I=5
$(5*255+4)*8 = 10232$ bits

Requirements NOT satisfied for current randomizer but will be with longer randomizer.

Spurious amplitudes must be no more than 6 dB over ideal PSD
~5 dB, Requirement Satisfied for

Requirement satisfied
Spurious Rate 40 Msps/10232 = 3.9 KHz
< 4KHz, Requirement Satisfied

Current Work

- Only PN patterns of the form $h(X) = 1 + X^p + X^M$ were considered.
  - Only one tap other than input and output for ease of calculation.
- No such primitive equation exists for PN14.
  - All others between 8 and 23 were considered.
- Consider a maximum CADU length of 16384 bits (will also consider longer)
- The original CCSDS papers considered an initial seed of all 1s but later papers considered other seeds. For PN 17 we found that all 1s will work.
- In the analysis the binary values were taken as +1 and -1 rather than 0 and 1.
- Truth table used is $+1 \times +1 = 1$, $-1 \times -1 = 1$, $+1 \times -1 = -1$, $-1 \times +1 = -1$
- Autocorrelation was calculate and normalized to make the peak 1.0.
- Eventually the “energy” is calculated for various CADU lengths to assess the several possible randomizers considered along with CADU lengths from 256 to 16384 bits.

Autocorrelation of Existing PN8 Randomizer

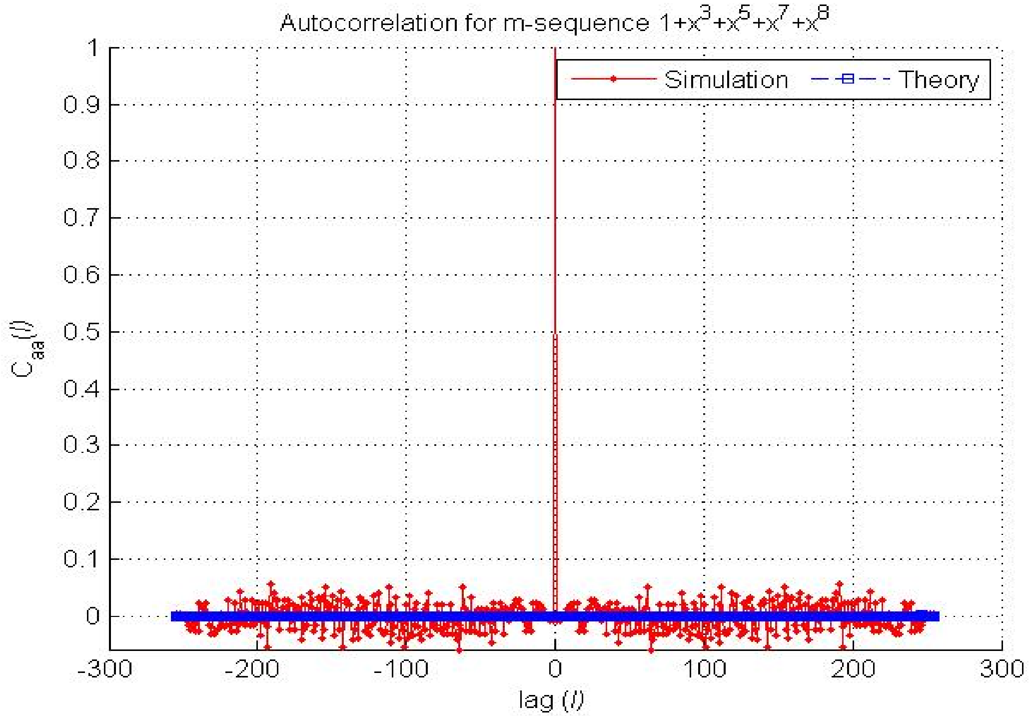


Figure 1a. Autocorrelation for current recommended PN8 MLS.

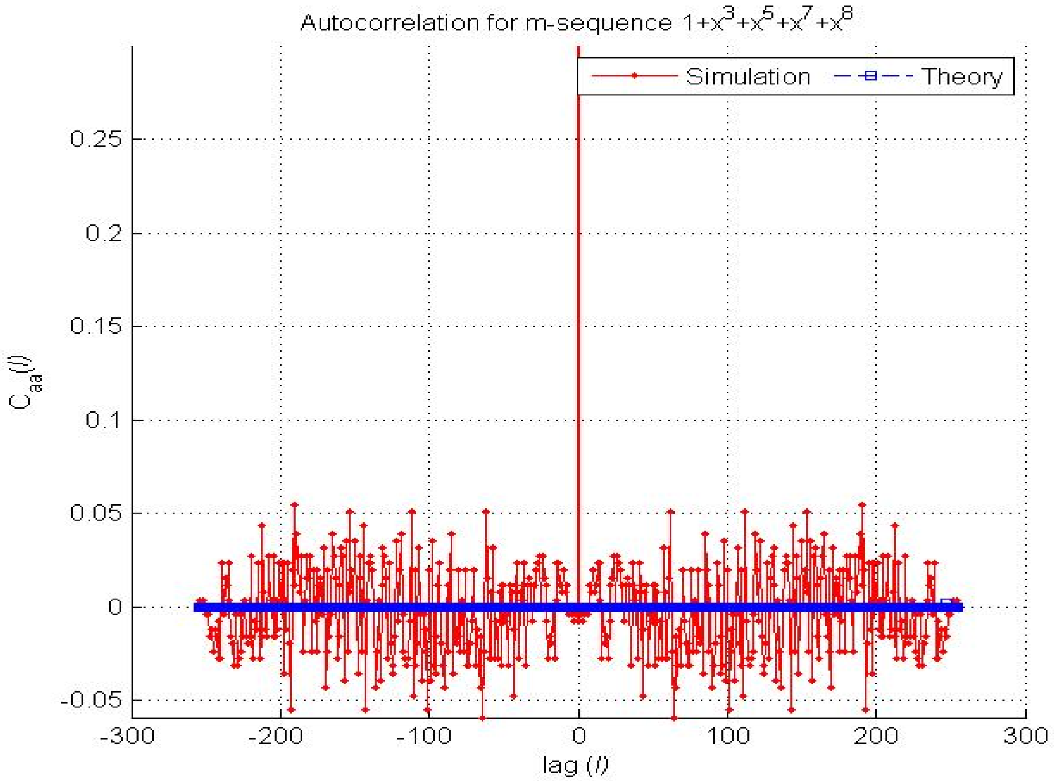


Figure 1b. Expanded correlation axis of Figure 1a. to show details of autocorrelation (current PN8 MLS).

Autocorrelation of Existing PN8 Randomizer when used with a 16 K bit CADU

Consider a CADU of length 16 K bits but made up of 64 PN 8 patterns for a total length of 16 K bits. Autocorrelation will peak when there is full overlap of the 64 PN 8 patterns and fall off with local peaks at increments of 255. The figure is shown with both a positive and negative shift or lag.

The correlation axis, (Y axis) is normalized to a peak of 1. Since the full overlap is 64 PN 8 patterns, the peak is 64 prior to normalization.

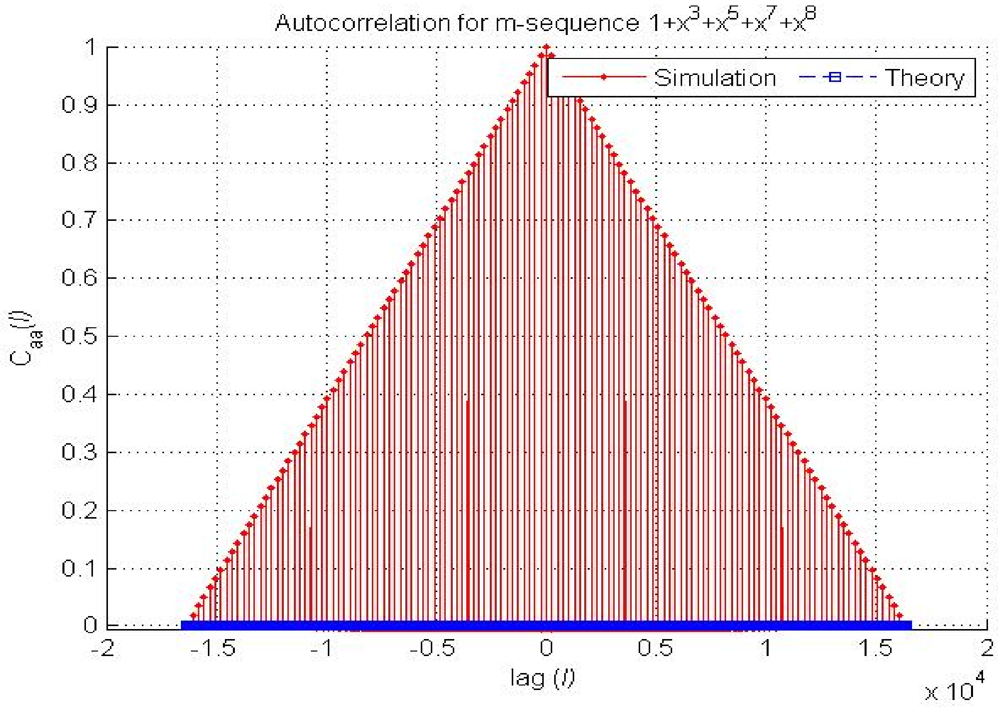


Figure 2. Autocorrelation of repeated application of PN8 MLS across CADU length of 2^{14} points.

To be presented by Howard Garon and Victor Sank at the Consultative Committee for Space Data Systems (CCSDS) Spring Technical Meetings, Gaithersburg, MD, April 9-13, 2018.

Autocorrelation of PN 10 Randomizer when used with a 16 K bit CADU

Consider a CADU of length 16 K bits but made up of 16 PN 10 patterns for a total length of 16 K bits. Autocorrelation will peak when there is full overlap of the 16 PN 10 patterns and fall off with local peaks at increments of 1023. The figure is shown with both a positive and negative shift or lag.

But with the longer pattern, there are less correlation spikes.

The correlation axis, (Y axis) is normalized to a peak of 1. Since the full overlap is 16 PN 10 patterns, the peak is 16 prior to normalization.

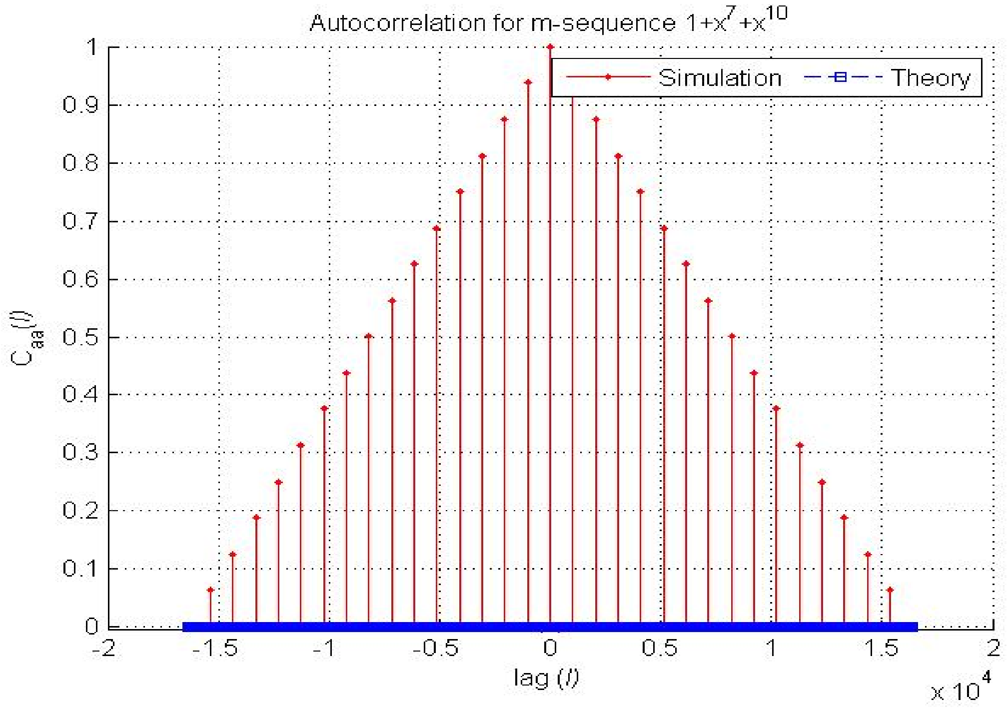


Figure 3. Autocorrelation of repeated application of PN10 MLS across CADU length of 2^{14} points.

Autocorrelation of PN 15 across 16 K bit CADU

Consider a CADU of length 16 K bits but made up of a PN 15 truncated to 16 K bits. Autocorrelation will peak when there is full overlap of the 16 PN bits and fall off on either side when there is partial overlap.

Note the lower off correlation value of 0.01 compared to the 0.05 for the currently recommended 255 length pattern.

The correlation axis, (Y axis) is normalized to a peak of 1.

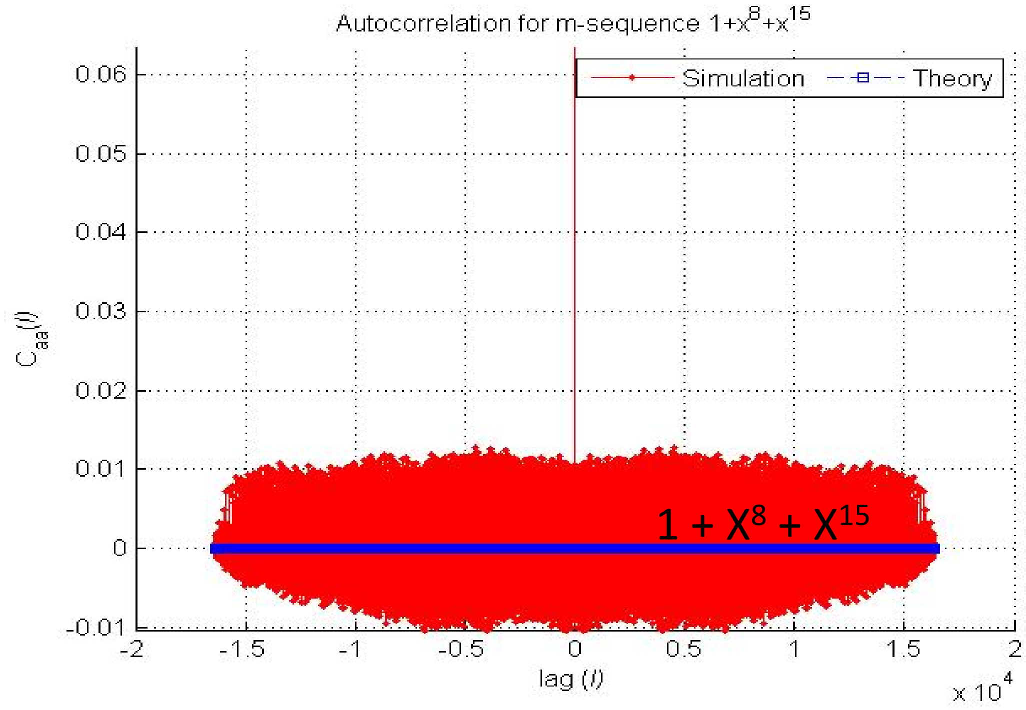


Figure 4. Autocorrelation of repeated application of PN 15 MLS across CADU length of 2^{14} points.

Coefficient of Determination: Autocorrelation for multiple CADU lengths

CADU of length 255 bits 16383 bits (symbols)

For the purpose of discussion, we have considered a CADU of max length 16 K bits = 2 K bytes which requires a randomizer of approximately the same length. Both shorter and longer CADUs will be used so we need to look at the performance of long randomizers as applied to short CADUs. We want the off correlation “energy” to be small. Here we look at the off correlation energy for CADUs of length 256 to 16 K symbols for each of 4 different randomizers.
Randomizers based on all 14 pairs of primitive polynomials with order between 8 and 23 with a single feedback tap were evaluated. This graph shows only 4 of them.

Note that the PN 10 case improves (gets smaller) as the CADU size goes from 256 to ~1000 bits, then degrades as the CADU gets larger. This is expected since a PN 10 pattern has its max randomness at its length of 1023).

A Tool for Pattern Evaluation

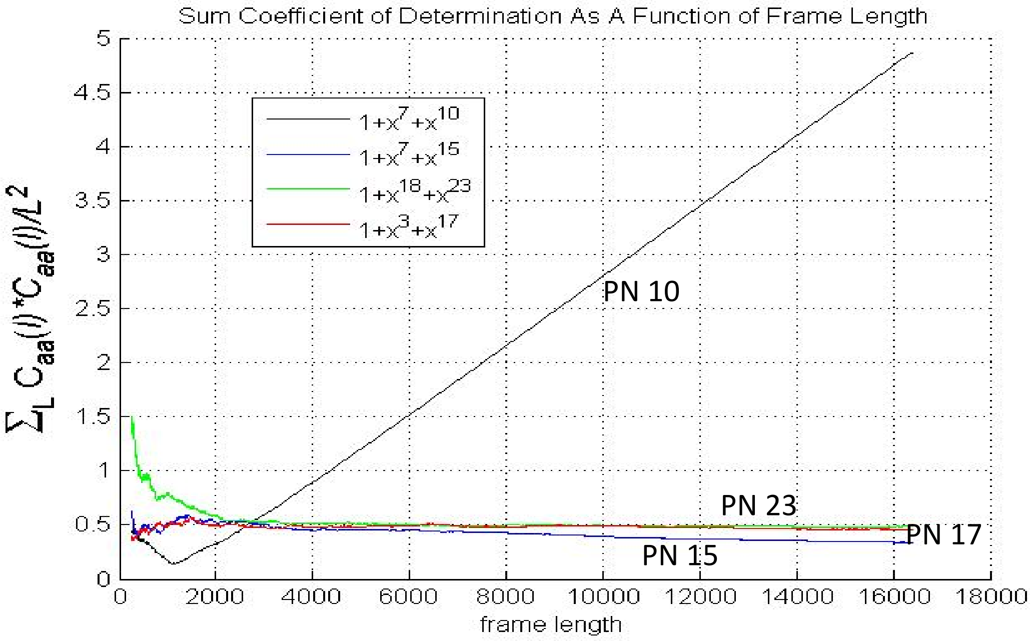


Figure 5. Metric of choice: Sum coefficient of determination as a function of CADU length.

Coefficient of Determination: Autocorrelation for multiple CADU lengths

CADU of length 255 bits 16383 bits (symbols)

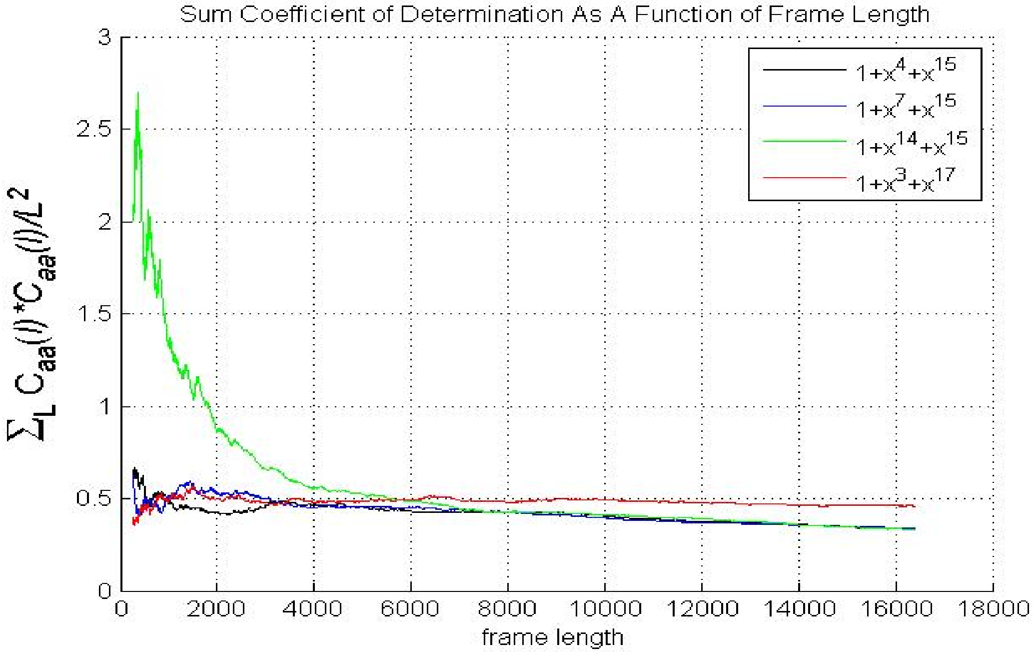


Figure 6a. Sum coefficient of determination as a function of CADU length.

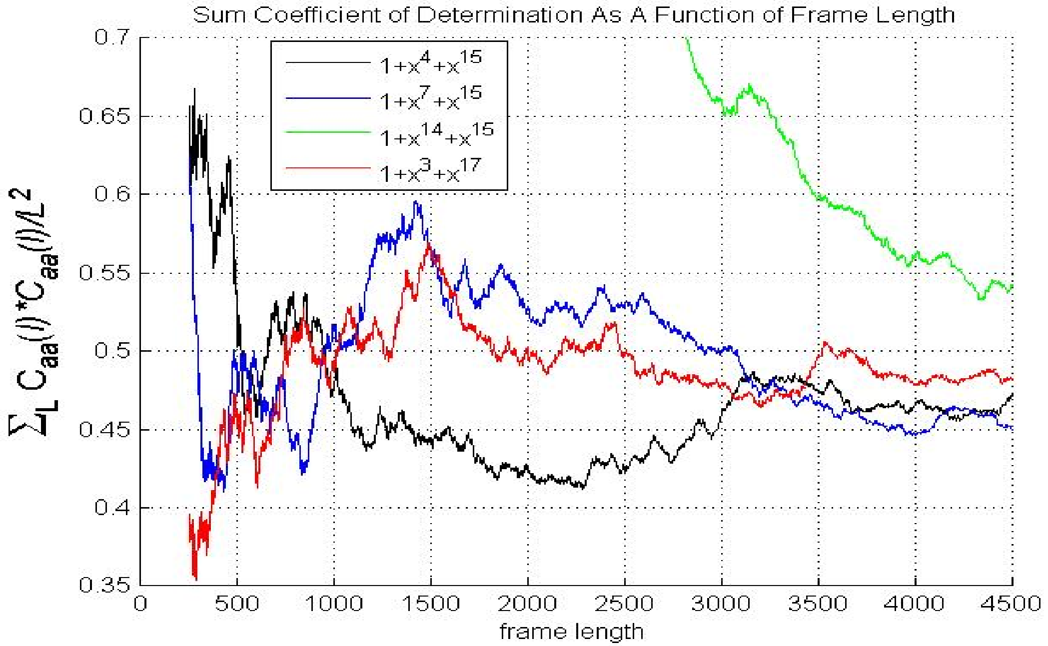
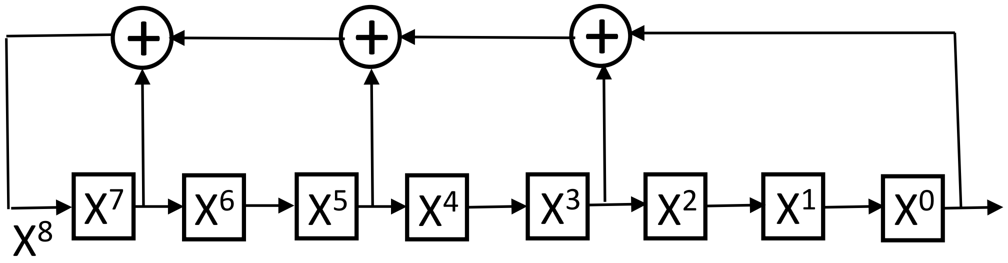


Figure 6b. Expanded axes to show details of Sum Coefficient of Determination for the shorter CADUs.

ESA PN Generator $h(X) = X^{15} + X^{14} + 1$

Although we prefer to label the PN generator as shown below, we have used to labeling as in the ESA paper to avoid possible confusion with their results.



Initialization not shown.
The taps here are at cells 8, 7, 5, 3, and 0
Which lead to a polynomial of
$X^8 + x^7 + x^5 + x^3 + x^0 = X^8 + x^7 + x^5 + x^3 + 1$

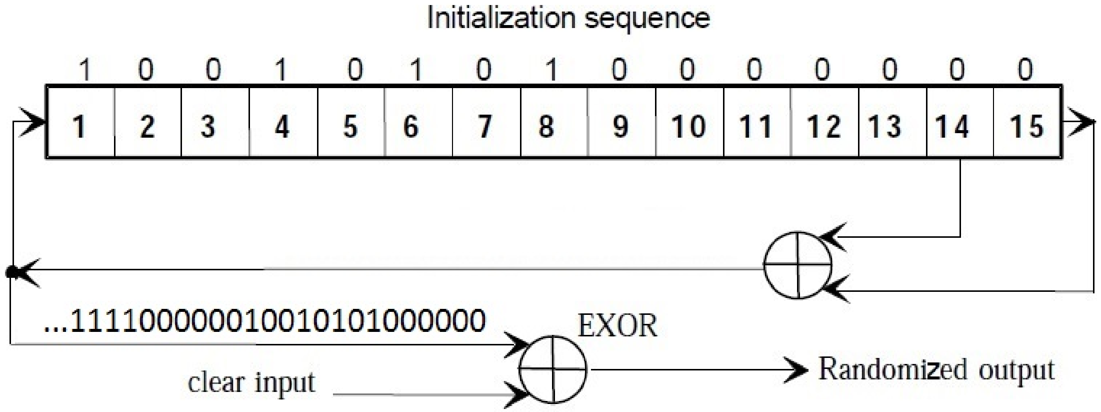
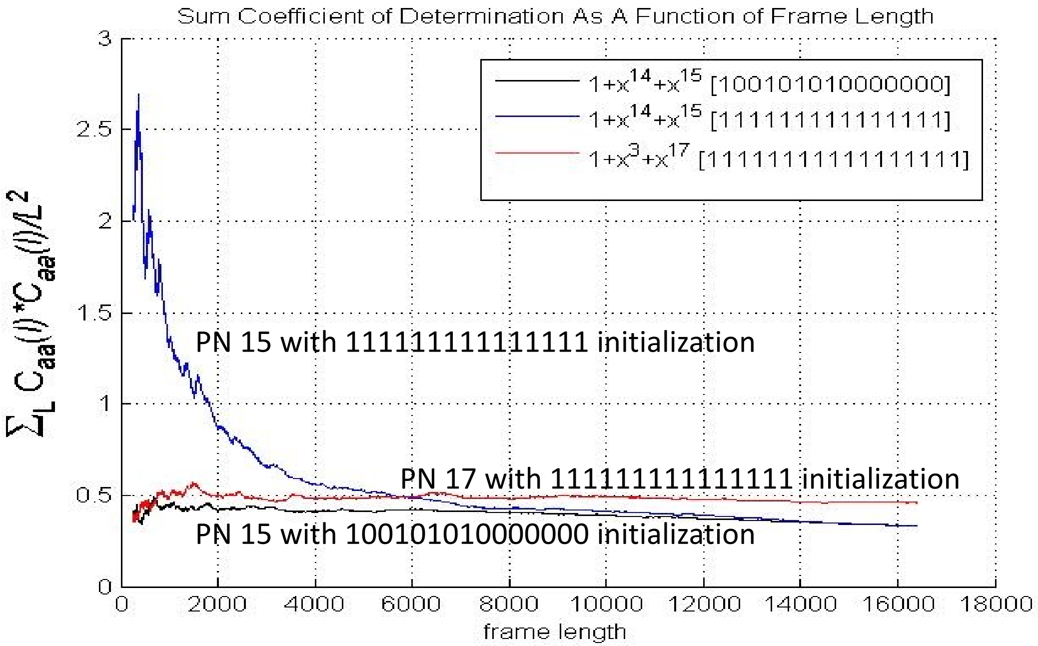


Figure 7. Possible implementation (Figure taken from “Draft ETSI EN 302 307 V1.3.1 (2012-11)”, European Telecommunications Standards Institute (ETSI), Sophia Antipolis Cedex, 2012.)

Coefficient of Determination as a Function of Initialization:

Autocorrelation of PN 15 (32 K length) across 16 K bit CADU

Initialization seed does not change pattern but does change the phase of the pattern. When using the all 1s seed, the pattern starts with the longest run of 1s. We see that with that seed, the performance of the ESA PN 15 is poor for short CADUs. ESA showed that using the same PN 15 pattern with a different seed, the performance with short CADUs is much better. Since the pattern is still the same, performance with longer CADUs remains essentially the same (good).



PN 15 with 111111111111111 initialization

PN 17 with 111111111111111 initialization

PN 15 with 100101010000000 initialization

Figure 8. Sum coefficient of determination as a function of CADU length (ESA recommendation).

To be presented by Howard Garon and Victor Sank at the Consultative Committee for Space Data Systems (CCSDS) Spring Technical Meetings, Gaithersburg, MD, April 9-13, 2018.

Coefficient of Determination:

Autocorrelation of PN 15 across 16 K bit CADU

Comparison of several patterns with CADUs from 255 bit
To 16383 bits in length.

A long pattern can have poor performance with
short CADUs as in the case of the $1 + x^{19} + x^{21}$ pattern.
But that same pattern taken in the opposite direction can
have much better performance, the $1 + x^2 + x^{21}$ pattern.

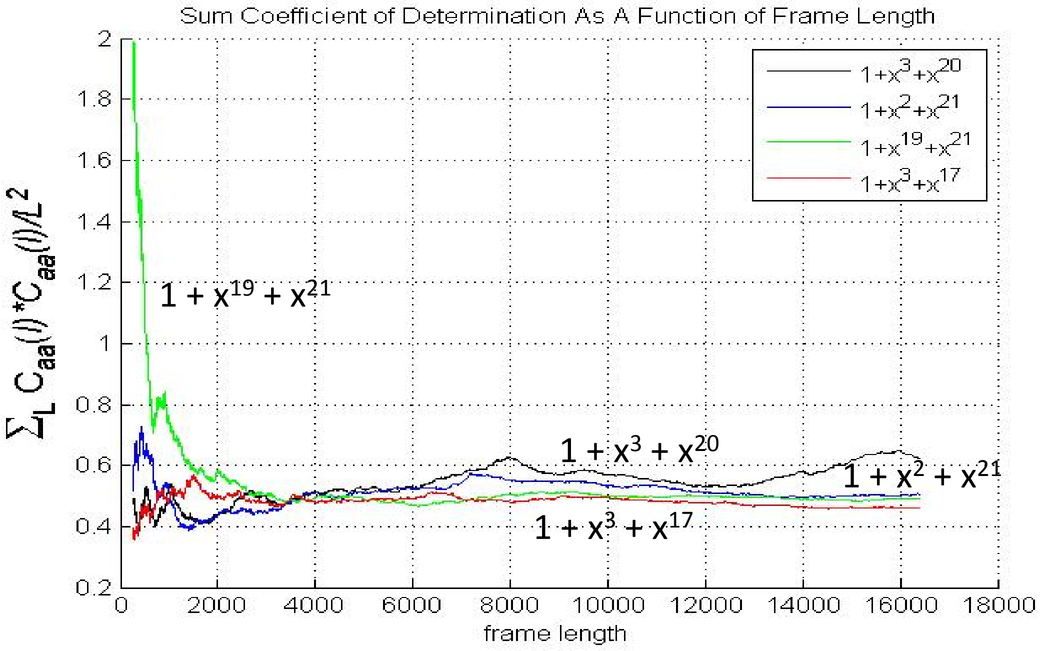


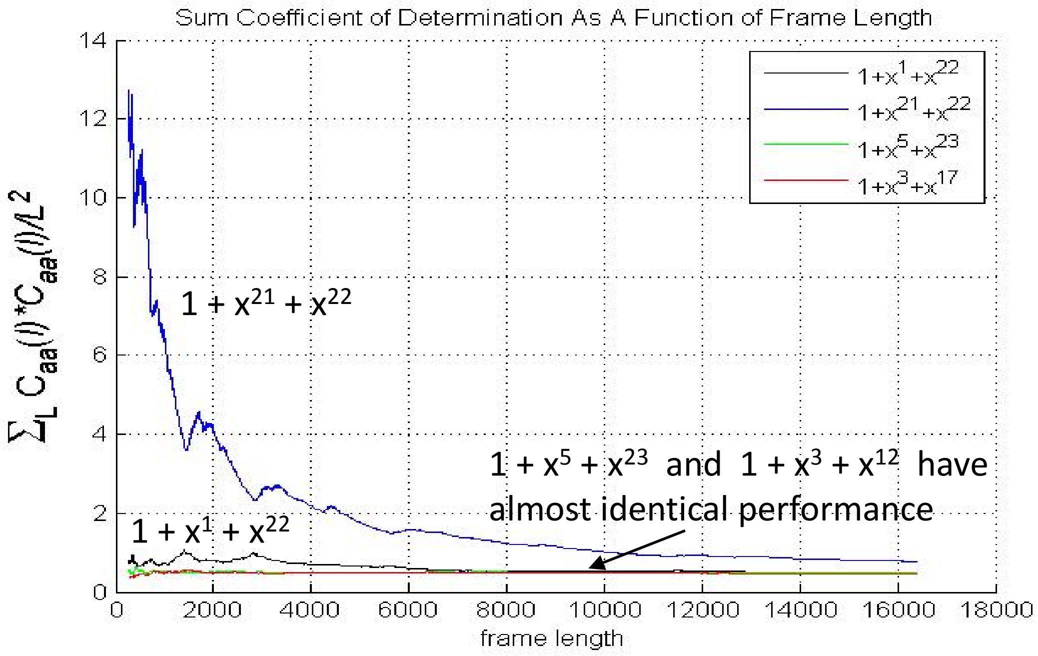
Figure 9. Sum coefficient of determination as a function of CADU length.

Coefficient of Determination:

Autocorrelation of PN 17, 22, and 23 across 16 K bit CADU

Similar results as previous slide with different patterns.

A long pattern can have poor performance with short CADUs as in the case of the $1 + x^{21} + x^{22}$ pattern. But that same pattern taken in the opposite direction can have much better performance, the $1 + x^{1} + x^{22}$ pattern.



$1 + x^{21} + x^{22}$

$1 + x^{5} + x^{23}$ and $1 + x^{3} + x^{12}$ have almost identical performance

$1 + x^{1} + x^{22}$

Figure 10. Sum coefficient of determination as a function of CADU length.

Coefficient of Determination:
Autocorrelation of PN 15 and 17 across 16 K bit CADU

Coefficient of Determination for CADU of length 16 K bits with 4 reasonably good PN patterns.
Expanded Y axis to show performance with short CADUs.
Both PN 15s are better than the PN 17s when examined up to only a length of 16 K bits since that covers half of the PN 15 pattern. For even longer CADUs, the performance of the PN 17s will first match then exceed that of the PN 15s.
Beyond the length of the PN, performance will degrade as seen for the PN 10 case in slide 14.

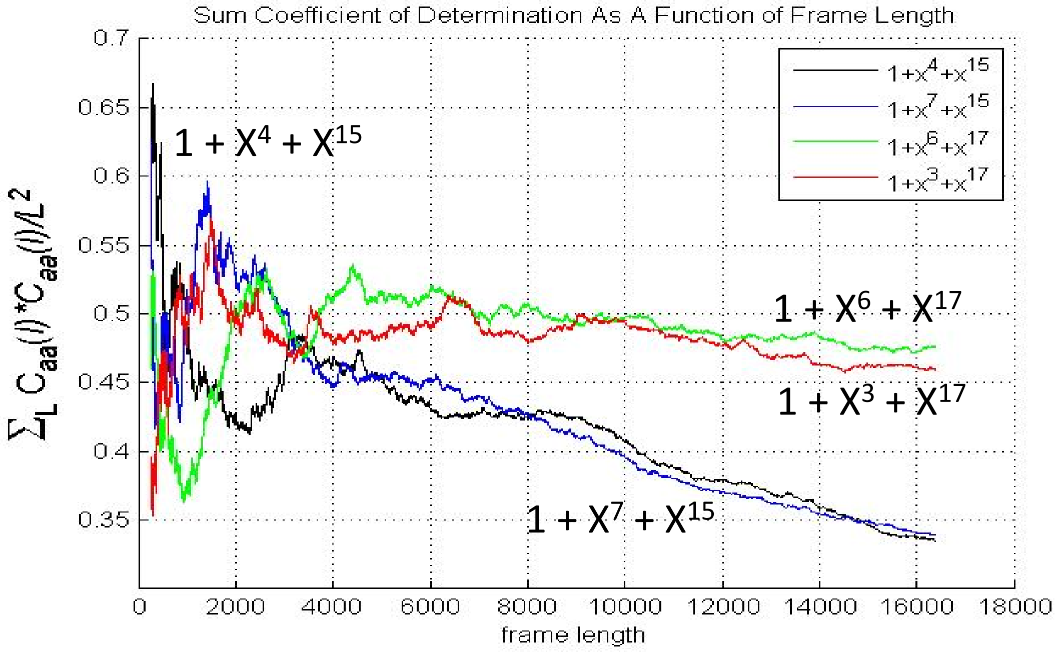


Figure 11. Four finalists not requiring special initialization.

Proposed selection for new CCSDS telemetry randomizer:

Autocorrelation of PN 17 across 16 K bit CADU

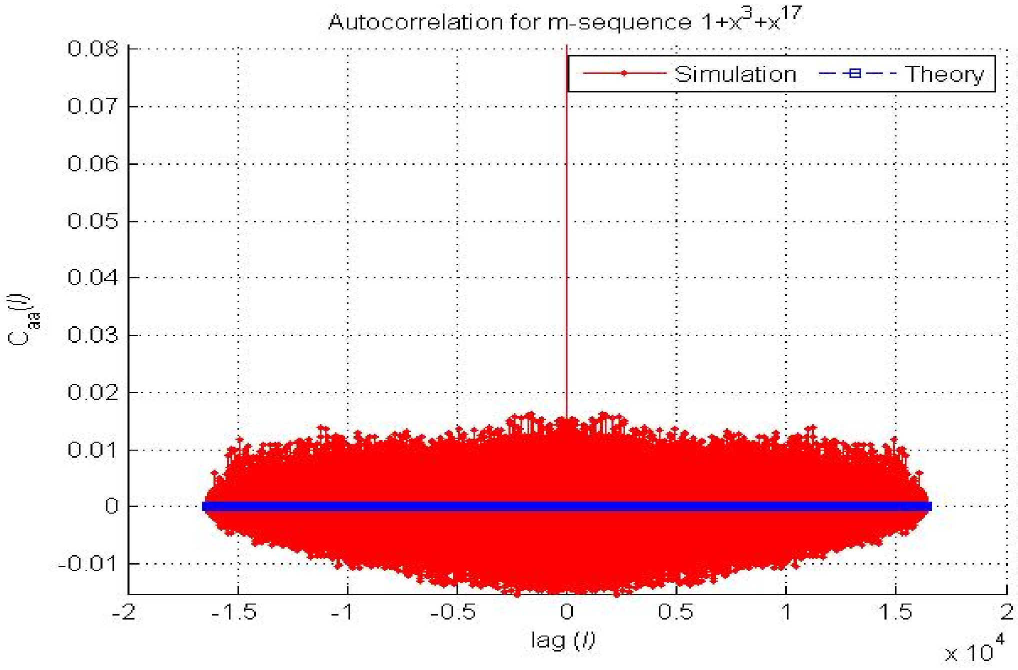
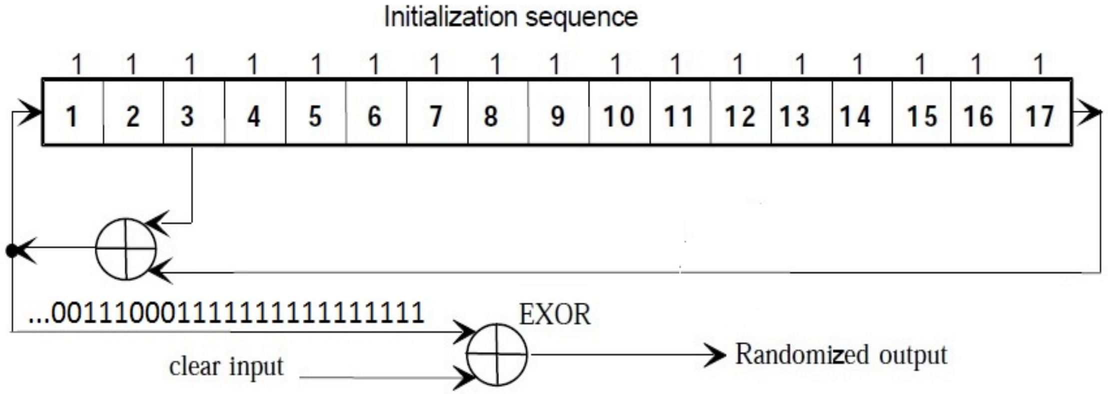


Figure 12. Autocorrelation of selected PN17 MLS: $1+x^3+x^{17}$ across CADU length of 2^{14} points.

Proposed selection for new CCSDS telemetry randomizer:

Generator for proposed PN 17 pattern

PN 17 with tap closest to the input out performs the same PN 17 in the reverse direction.
When starting with an all 1s initialization, having the tap closest to the input causes the pattern to get random sooner. This may be a factor in the improved performance with short CADUs.



Same pattern but In opposite direction
…10000000000000011111111111111111

Figure 13. Recommended MLS ($1+x^3+x^{17}$) for randomization along with suggested initialization.

Recommendation and Summary

Under the guidelines we considered here there are multiple maximal length sequences under GF(2) which appear attractive. Although there may be mitigating reasons why another MLS sequence would be selected, one sequence in particular,

$PN(x) = 1 + x^3 + x^{17}$,

possesses a combination of desired properties which offsets it from the others. The autocorrelation for this MLS is shown in figure 12 and is quite similar to the autocorrelation shown in figure 4 for $1 + x^8 + x^{15}$. The polynomial is very simple in construction, employs only three terms (one feedback register) and already displays close to optimum auto-correlation properties with all shift registers initialized to one. Coupled with the prospect that this sequence length (2^{17}-1) can anticipate much greater CADU lengths beyond our restrictions here, these properties make the sequence attractive to promulgate and implement in practice. Our new recommendation should aid in signal acquisition by supporting bit/symbol synchronization as well as minimizing decoder false lock.

Back up slides

Randomizer for High Data Rates

Coefficient of Determination:

Autocorrelation of PN 17 across 16 K bit CADU

Comparison of the use of the first 16K bits of the PN 17 pattern $1 + X^3 + X^{17}$ and the same pattern but taken in the opposite direction, $1 + X^{14} + X^{17}$. Since there in ambiguity when stating the equation and knowing the direction of the pattern, we use the diagram in figure 13 to remove that ambiguity.

In order to make comparison with previous work, we Have used the shift register cell numbering as in that Work. Our preference is to number the cells as shown on the right of slide 3, where the tapped cells directly correlate with the exponents in the polynomial.

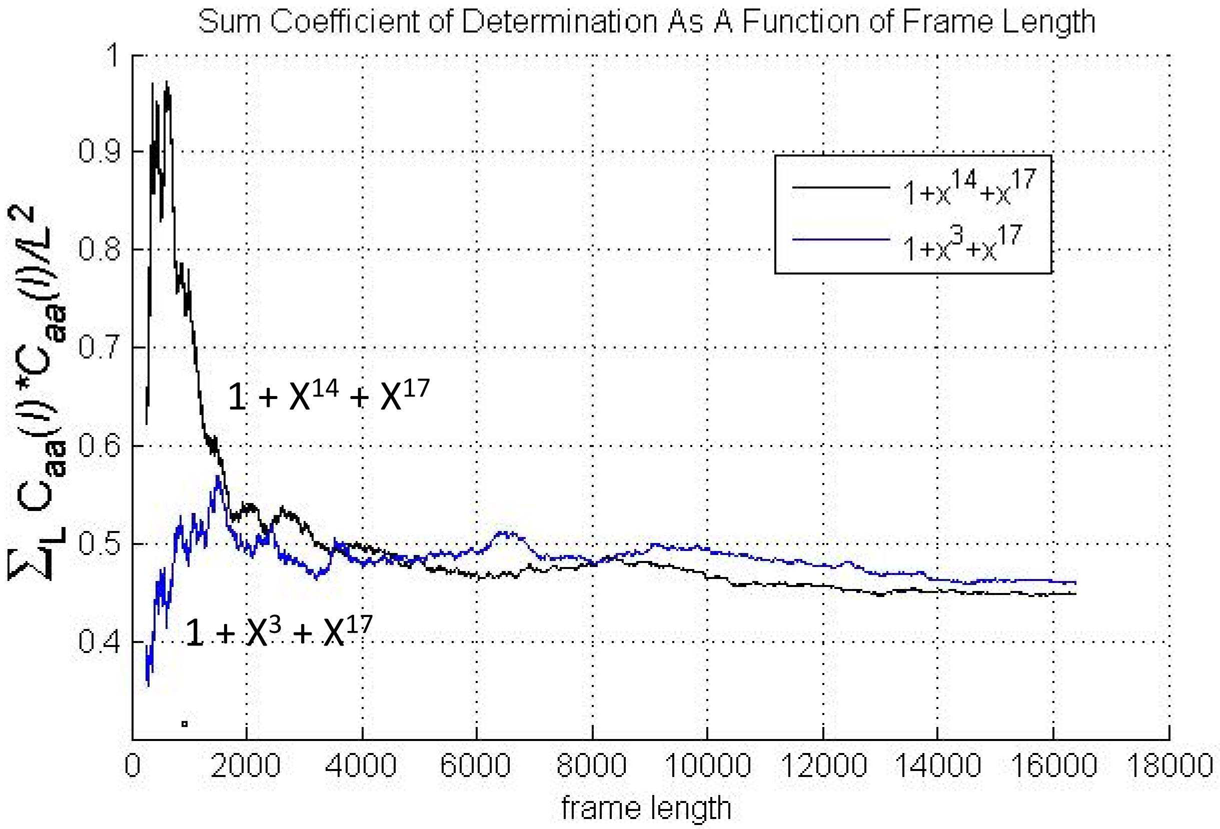


Figure 14. Recommended MLS ($1+x^3+x^{17}$) for randomization showing the better performance for short CADUs. For longer CADUs the performance of the two patterns will converge.

References:

[1] *TM Synchronization and Channel Coding*. Recommendation for Space Data System Standards, CCSDS 131.0-B-3. Blue Book. Issue 3. September 2017.

[2] *TM Synchronization and Channel Coding – Summary of Concept and Rationale.* CCSDS 230.1-G-2. Green Book. Issue 2. November 2012.

[3] O. Alvarez and G. Lesthievent, “Pseudo-Random Codes for High Data Rate Telemetry: Analysis and New Proposal”, CCSDS RF & Modulation & Channel Coding Working Groups, Roma, 12 June 2006.

[4] M. Baldi, G. P. Calzolari, F. Chiaraluce, and R. Garello, “Randomizer for High Data Rates: Some Proposals against the Problem of Spectral Spurious”, CCSDS Coding & Synchronization Working Group, Fall Meeting, Berlin, 13 October 2008.

[5] R. Garello, M. Baldi, F. Chiaraluce, “Randomizer for High Data Rates”, Politecnico di Torino, European Space Agency Contract Report, ESOC Contract No. 20959/07/D/MRP, March 2009.

[6] R. Garello, M. Baldi, G. P. Calzolari (ESA/ESOC), “Summary of High Data Rate Randomizer Investigations”, CCSDS SLS-Coding & Synchronization Working Group, Spring Meeting, Colorado Springs, 21 April 2009.

[7] “Draft ETSI EN 302 307 V1.3.1 (2012-11)”, European Telecommunications Standards Institute (ETSI), Sophia Antipolis Cedex, 2012.