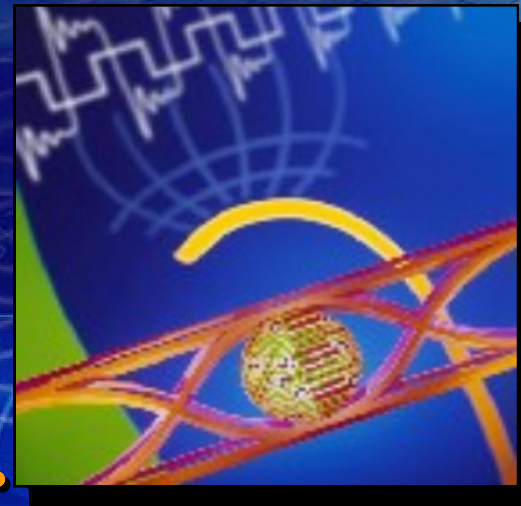
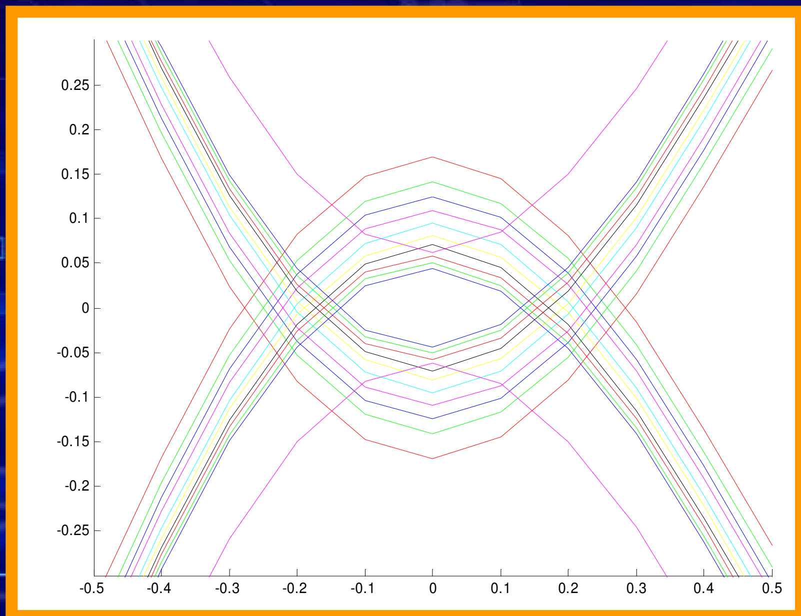
IBIS-AMI with Different Languages

IBIS Summit, DesignCon, February 2008

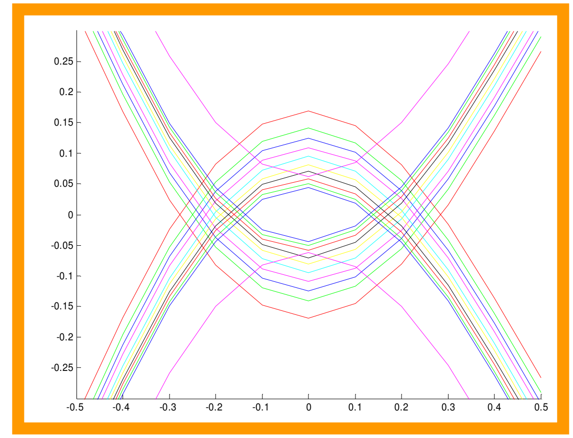




Arpad Muranyi

Mentor Graphics®

IBIS-AMI with Different Languages



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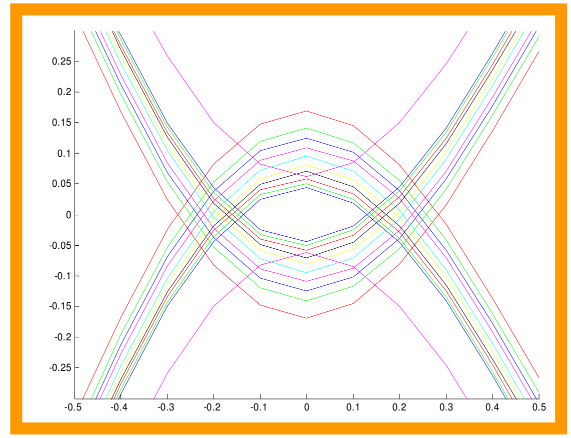
1. Review: The IBIS-AMI BIRD and Toolkits
2. The language of IBIS-AMI models
3. Comments on the Tx model in C
4. The Tx model in VHDL-AMS
5. The Tx model in Matlab
6. Benchmarks and Conclusions

The IBIS-AMI BIRD and Toolkits

- **The IBIS-ATM committee spent about two years to define and write the IBIS-AMI BIRD**
  - **BIRD 104.1 was approved on Nov. 30, 2007**
    http://www.vhdl.org/pub/ibis/birds/bird104.1.txt
  - **two free toolkits have been posted**
    http://www.vhdl.org/pub/ibis/macromodel_wip/archive/20080122/cadence/Cadence_IBIS_AMI_Evaluation_Toolkit_v2_0.zip
    http://www.vhdl.org/pub/ibis/macromodel_wip/archive/20080116/sisoft/SiSoft_IBIS-AMI_Eval_Toolkit_v2_03.zip
- **Some IC vendors already have or are considering IBIS-AMI models for their SERDES products**
- **BIRD 104.1 is not part of the IBIS specification yet**
  - **expected to be included in the next version (v5.0)**

IBIS-AMI with Different Languages



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1. **Overview: The IBIS-AMI BIRD and Toolkits**
2. **The language of IBIS-AMI models**
3. **Comments on the Tx model in C**
4. **The Tx model in VHDL-AMS**
5. **The Tx model in Matlab**
6. **Benchmarks and Conclusions**

The language of IBIS-AMI models

```
|==============================================================================
|    Keywords: [Algorithmic Model], [End Algorithmic Model]
|    Required: No
|
| Description: Used to reference an external compiled model.  This compiled
|              model encapsulates signal processing functions.  In the case
|              of a receiver it may additionally include clock and data
|              recovery functions.  The compiled model can receive and modify
|              waveforms with the analog channel, where the analog channel
|              consists of the transmitter output stage, the transmission
|              channel itself and the receiver input stage.  This data
|              exchange is implemented through a set of software functions.
|              The signature of these functions is elaborated in section 10
|              of this document.  The function interface must comply with
|              ANSI 'C' language.
```

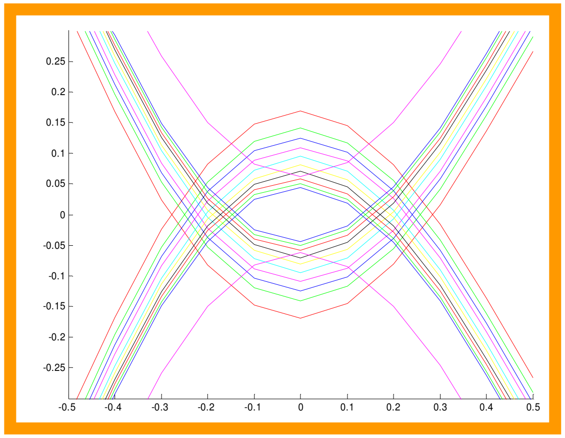
It has been stated in meetings and presentations that the IBIS-AMI model can be written in any language as long as its interface complies with ANSI C (possibly using wrappers)

The toolkit model examples are written in ANCI C

ANCI C - a modeling language?

- Who will write models?
  - system or circuit designers are usually electronic engineers
  - communications experts are good with filter design, channel analysis techniques, etc…
- Problem:
  - no matter how brilliant the above people are, they may not have the experience in implementing FIR filters or convolution algorithms in ANSI C
- Anybody interested in building a home-made car before driving off to a vacation with it?

IBIS-AMI with Different Languages



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Comments on the Tx model in C

```
IBIS_AMI_API long AMI_Init( double *impulse_matrix,
                            long row_size,
                            long aggressors,
                            double sample_interval,
                            double bit_time,
                            char *AMI_parameters_in,
                            char **AMI_parameters_out,
                            void **AMI_memory_handle,
                            char **msg ) {
   AtmTxModel *self;
   double samp_dbl, norm, *tmp_dbl;
   int indx, yndx, item_count;
   ParamListItem taps[4] = { { "-1", ami_double_type, 0 },
                             { "0",  ami_double_type, 0 },
                             { "1",  ami_double_type, 0 },
                             { "2",  ami_double_type, 0 } };
   ParamListItem param[2] = { { "tap_filter", ami_list_type, 0 },
                              { "tx_swing",   ami_double_type,   0 } };
   ParamList tap_list   = { "tap_filter",  4, &taps[0] };
   ParamList param_list = { "IBIS_AMI_Tx", 2, &param[0] };

   //Default parameter values
   taps[0].p_val.dbl_val = 0;
   taps[1].p_val.dbl_val = 1;
   taps[2].p_val.dbl_val = 0;
   taps[3].p_val.dbl_val = 0;
```

Color code:

black: "normal" stuff
green: still able to handle it
red: too much for ***me*** (EE)

Comments on the Tx model in C - cont'd

```
//Default parameter values
param[0].p_val.ptr_val = (void*)&tap_list;
param[1].p_val.dbl_val = 0.8;

self = (AtmTxModel*)malloc( sizeof( AtmTxModel ) );
*AMI_memory_handle = (void*)self;

//Parse the parameter string
item_count = 0;
if( AMI_parameters_in ) { item_count = ParseTree( AMI_parameters_in, param_list );
}

self->msg = (char*)malloc( 68*sizeof( char ) );
memset( self->msg, 0, 68*sizeof( char ) );
sprintf( self->msg, "INFO: Configured %d items through parameter string.", item_count );
*msg = self->msg;

//Normalize the tap coefficients.
norm = fabs( taps[0].p_val.dbl_val ) +
       fabs( taps[1].p_val.dbl_val ) +
       fabs( taps[2].p_val.dbl_val ) +
       fabs( taps[3].p_val.dbl_val ) ;
taps[0].p_val.dbl_val /= norm;
taps[1].p_val.dbl_val /= norm;
taps[2].p_val.dbl_val /= norm;
taps[3].p_val.dbl_val /= norm;
```

Comments on the Tx model in C - cont'd

```
//Echo the parameters back out
*AMI_parameters_out = GrowTree( param_list );

self->taps[0]          = taps[0].p_val.dbl_val;
self->taps[1]          = taps[1].p_val.dbl_val;
self->taps[2]          = taps[2].p_val.dbl_val;
self->taps[3]          = taps[3].p_val.dbl_val;
self->swing            = param[1].p_val.dbl_val;
self->row_size         = row_size;
self->out_buf          = 0;
self->buf_size         = 0;
self->last_in          = 0;
self->sample_interval = sample_interval;
self->bit_time         = bit_time;
self->params_out       = *AMI_parameters_out;

samp_dbl = bit_time/sample_interval - 0.5;
self->samples = 1;
while( self->samples < samp_dbl ) {
   self->samples++;
}
```

"round to the nearest" function…

Comments on the Tx model in C - cont'd

```
tmp_dbl = (double*)malloc( row_size*(aggressors+1)*sizeof( double ) );
for( yndx = 0; yndx < aggressors+1; yndx++ ) {
   for( indx = 0; indx < row_size; indx++ ) {
      tmp_dbl[ indx+row_size*yndx ] =
                           self->taps[0]*impulse_matrix[ indx+row_size*yndx ];
      if( indx >= self->samples ) {
         tmp_dbl[ indx+row_size*yndx ] +=
            self->taps[1]*impulse_matrix[ indx+row_size*yndx-self->samples ];
      }
      if( indx >= 2*self->samples ) {
         tmp_dbl[ indx+row_size*yndx ] +=
          self->taps[2]*impulse_matrix[ indx+row_size*yndx-2*self->samples ];
      }
      if( indx >= 3*self->samples ) {
         tmp_dbl[ indx+row_size*yndx ] +=
          self->taps[3]*impulse_matrix[ indx+row_size*yndx-3*self->samples ];
      }
      tmp_dbl[ indx+row_size*yndx ] *= self->swing;
   }
}
memcpy( impulse_matrix, tmp_dbl, row_size*(aggressors+1)*sizeof( double ) );
free( tmp_dbl );

//Calculate the step response
self->step_response = (double*)malloc( row_size*sizeof( double ) );
self->step_response[0] = sample_interval * impulse_matrix[0];
for( indx = 1; indx < row_size; indx++ ) {
   self->step_response[indx] = self->step_response[indx-1] + sample_interval * impulse_matrix[indx];
}
```

4-tap FIR filter

Comments on the Tx model in C - cont'd

```c
IBIS_AMI_API long AMI_GetWave( double *wave_in,
                               long wave_size,
                               double *clock_times,
                               char **AMI_parameters_out,
                               void *AMI_memory ) {
   int tmp_size, indx, yndx, clock_dx;
   double *tmp_dbl, step_size;
   AtmTxModel *self = (AtmTxModel*)AMI_memory;

   //Create an extended array to compute from.
   tmp_size = self->row_size + wave_size;
   if( self->buf_size < tmp_size ) {
      tmp_dbl = (double*)malloc( tmp_size*sizeof( double ) );
      memset( tmp_dbl, 0, tmp_size*sizeof( double ) );
      //Resize if necessary
      if( self->out_buf != 0 ) {
         memcpy( tmp_dbl, self->out_buf, self->buf_size*sizeof( double ) );
         free( self->out_buf );
      }
      self->out_buf  = tmp_dbl;
      self->buf_size = tmp_size;
   }
   else {
      tmp_dbl = self->out_buf;
   }
```

Comments on the Tx model in C - cont'd

```
//Compute the response.
clock_dx = 0;
for( indx = 0; indx < wave_size; indx++ ) {
   if( wave_in[ indx ] * self->last_in < 0 ){
      clock_times[ clock_dx++ ] = gw_time + (indx-0.5)*self->sample_interval;
   }
   if( wave_in[ indx ] != self->last_in ) { //Add step response
      step_size = wave_in[ indx ] - self->last_in;
      for( yndx = 0; yndx < self->row_size; yndx++ ) {
         tmp_dbl[ indx+yndx ] += step_size * self->step_response[ yndx ];
      }
      for( yndx = indx+self->row_size; yndx < self->buf_size; yndx++ ) {
         tmp_dbl[ yndx ] += step_size *
                           self->step_response[ self->row_size-1 ];
      }
   }
   self->last_in = wave_in[ indx ];
   wave_in[ indx ] = tmp_dbl[ indx ]; //Save the output
}

//Terminate the list of clock ticks
clock_times[ clock_dx ] = -1;
```

using a step response as an input, this makes a convolution function

Comments on the Tx model in C - cont’d

```
   //Terminate the list of clock ticks
   clock_times[ clock_dx ] = -1;

   //Save the remaining response for the next block of data
   for( indx = 0; indx < self->row_size; indx++ ) {
      tmp_dbl[ indx ] = tmp_dbl[ indx+wave_size ];
   }
   for( ; indx < self->buf_size; indx++ ) {
      tmp_dbl[ indx ] = tmp_dbl[ self->row_size-1 ];
   }

   gw_time += wave_size*self->sample_interval;

   return 1;
}

IBIS_AMI_API long AMI_Close( void *AMI_memory ) {
   AtmTxModel *self = (AtmTxModel*)AMI_memory;
   free( self->step_response );
   free( self->out_buf );
   free( self->params_out );
   free( self->msg );
   free( self ); //"The truth will set you free."
   return 1;
}
```

“garbage collection”

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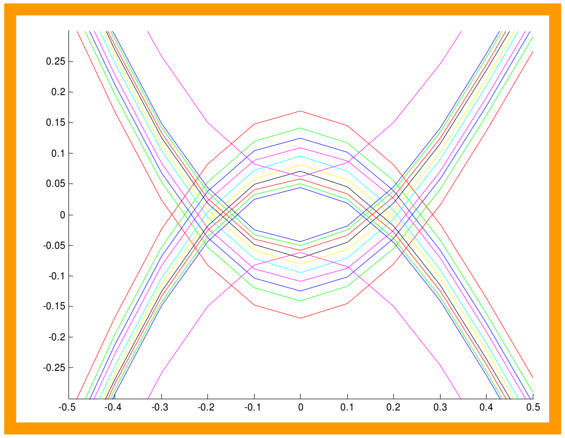

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Other language candidates

- VHDL-AMS and Verilog-AMS in IBIS
  - multi-lingual extensions (section 6b) available starting IBIS v4.1 (since February 2004)
- Matlab is quite popular for SERDES buffer and/or system development:
  - StatEye (public domain) was written in Matlab
  - lots of other, home grown tools have been developed by major IC companies

The Tx model in VHDL-AMS

```
--==============================================================================
impure function AMI_init (FileName       : string  := "";
                          DoStepResponse : boolean := false;
                          Debug          : boolean := false) return real_vector is
--------------------------------------------------------------------------------
  constant  RowSize         : integer := FileRead(FileName, "row_size",        1024);
  constant  Aggressors      : integer := FileRead(FileName, "aggressors",      0);
  constant  SampleInterval  : real    := FileRead(FileName, "sample_interval", 2.50E-11);
  constant  BitTime         : real    := FileRead(FileName, "bit_time",        2.00E-10);
  constant  TxSwing         : real    := FileRead(FileName, "tx_swing",        1.0);

  constant  TapCoeff        : real_vector := FileRead(FileName, "tap_filter",             (0.0, 1.0, 0.0, 0.0));
  constant  ImpulseMatrix   : real_vector := FileRead(FileName, "Time,impulse(primary)", (1.0, 2.0, 3.0, 4.0));

  variable  TapCoeffNorm    : real_vector(TapCoeff'range) := TapCoeff;
  variable  Norm            : real                        := 0.0;
  variable  Samples         : integer := 1;
  variable  Samp_dbl        : real    := 0.0;

  variable  i               : integer := 0;
  variable  indx            : integer := 0;
  variable  yndx            : integer := 0;
  variable  ImpResponse     : real_vector(ImpulseMatrix'range) := (others => 0.0);
  variable  StepResponse    : real_vector(ImpulseMatrix'range) := (others => 0.0);
--------------------------------------------------------------------------------
```

Note:

The parameter tree parser was not implemented in the file I/O functions of this VHDL-AMS example

The Tx model in VHDL-AMS - cont'd

```
begin
  ---------------------------------------------------------------------------
  -- Normalize the tap coefficients
  ---------------------------------------------------------------------------
  for i in TapCoeff'range loop
    Norm := Norm + abs(TapCoeff(i));
  end loop;
  for i in TapCoeff'range loop
    TapCoeffNorm(i) := TapCoeff(i) / Norm;
  end loop;
  ---------------------------------------------------------------------------
  -- Calculate samples per bit
  ---------------------------------------------------------------------------
  Samp_dbl := BitTime / SampleInterval - 0.5;
  while (real(Samples) < Samp_dbl) loop
    Samples := Samples + 1;
  end loop;
  ---------------------------------------------------------------------------
```

"round to the nearest" function…

The Tx model in VHDL-AMS - cont'd

```
----------------------------------------------------------------------------
-- Calculate equalized impulse response
----------------------------------------------------------------------------
for yndx in 0 to Aggressors loop
  for indx in 0 to RowSize-1 loop
    ImpResponse(indx+RowSize*yndx) := TapCoeffNorm(0)*ImpulseMatrix(indx+RowSize*yndx);
    if (indx >= Samples) then
      ImpResponse(indx+RowSize*yndx) := ImpResponse(indx+RowSize*yndx)
                                       + TapCoeffNorm(1)*ImpulseMatrix(indx+RowSize*yndx-Samples);
    end if;
    if (indx >= 2*Samples) then
      ImpResponse(indx+RowSize*yndx) := ImpResponse(indx+RowSize*yndx)
                                       + TapCoeffNorm(2)*ImpulseMatrix(indx+RowSize*yndx-2*Samples);
    end if;
    if (indx >= 3*Samples) then
      ImpResponse(indx+RowSize*yndx) := ImpResponse(indx+RowSize*yndx)
                                       + TapCoeffNorm(3)*ImpulseMatrix(indx+RowSize*yndx-3*Samples);
    end if;
    ImpResponse(indx+RowSize*yndx) := ImpResponse(indx+RowSize*yndx) * TxSwing;
  end loop;
end loop;
```

4-tap FIR filter

The Tx model in VHDL-AMS - cont'd

```
  if (DoStepResponse = true) then
    --------------------------------------------------------------------------
    -- Calculate step response
    --------------------------------------------------------------------------
    StepResponse(0) := SampleInterval * ImpResponse(0);
    for indx in 1 to RowSize-1 loop
      StepResponse(indx) := StepResponse(indx-1) + SampleInterval * ImpResponse(indx);
    end loop;

    -- Return step response
    return StepResponse;
    --------------------------------------------------------------------------
  else
    -- Return impulse response
    return ImpResponse;
    --------------------------------------------------------------------------
  end if;
  ----------------------------------------------------------------------------
end function AMI_init;
--============================================================================
```

Return either the Step Response

or the

Impulse Response

The Tx model in VHDL-AMS - cont'd

```
--==============================================================================
impure function AMI_getwave (IniFile        : string  := "";
                             Debug          : boolean := false) return real_vector is
--------------------------------------------------------------------------------
  constant  RowSize        : integer  := FileRead(IniFile, "row_size",        1024);
  constant  RegisterLength : integer  := FileRead(IniFile, "register_length", 7);
  constant  BitTime        : real     := FileRead(IniFile, "bit_time",        2.00E-10);
  constant  SampleInterval : real     := FileRead(IniFile, "sample_interval", 2.50E-11);
  constant  StopTime       : real     := FileRead(IniFile, "stop_time",       4.00E-08);
  constant  WaveSize       : integer  := integer(floor(StopTime / SampleInterval));
  constant  TempSize       : integer  := RowSize + WaveSize;

--  constant  WaveIn         : real_vector := FileRead(WfmFile, "Time,wave_in", ( 1.0, 2.0, 3.0, 4.0));
  constant  WaveIn         : real_vector := PRBS(RegisterLength, BitTime, SampleInterval, StopTime);
  constant  StepResponse   : real_vector := AMI_init(IniFile, true, false);

  variable  i              : integer := 0;
  variable  Clock_indx     : integer := 0;
  variable  indx           : integer := 0;
  variable  yndx           : integer := 0;
  variable  GwTime         : real    := 0.0;
  variable  StepSize       : real    := 0.0;
  variable  LastIn         : real    := 0.0;
  variable  ClockTimes     : real_vector(WaveIn'range)    := (others => 0.0);
  variable  ReturnVec      : real_vector(0 to TempSize-1) := (others => 0.0);
  variable  tmp_dbl        : real_vector(ReturnVec'range) := (others => 0.0);
--------------------------------------------------------------------------------
```

<u>WaveIn</u> can be read from a data file or generated by a PRBS function

The Tx model in VHDL-AMS - cont'd

```
begin
  ---------------------------------------------------------------------------
  -- Compute the response
  ---------------------------------------------------------------------------
  for indx in WaveIn'range loop
    -- Save the time of each edge of WaveIn in ClockTimes
    if (WaveIn(indx)*LastIn < 0.0 ) then
      ClockTimes(Clock_indx) := GwTime + (real(indx)-0.5) * SampleInterval;
      Clock_indx := Clock_indx + 1;
    end if;

    if (WaveIn(indx) /= LastIn) then
      -- Add step response
      StepSize := WaveIn(indx) - LastIn;
      for yndx in 0 to RowSize-1 loop
        ReturnVec(indx+yndx) := ReturnVec(indx+yndx) + StepSize * StepResponse(yndx);
      end loop;
      for yndx in indx+RowSize to TempSize-1 loop
        ReturnVec(yndx) := ReturnVec(yndx) + StepSize * StepResponse(RowSize-1);
      end loop;
    end if;

    LastIn := WaveIn(indx);
  end loop;

  -- Terminate the list of clock ticks
  ClockTimes(Clock_indx) := -1.0;
```

using a step response as an input, this makes a convolution function

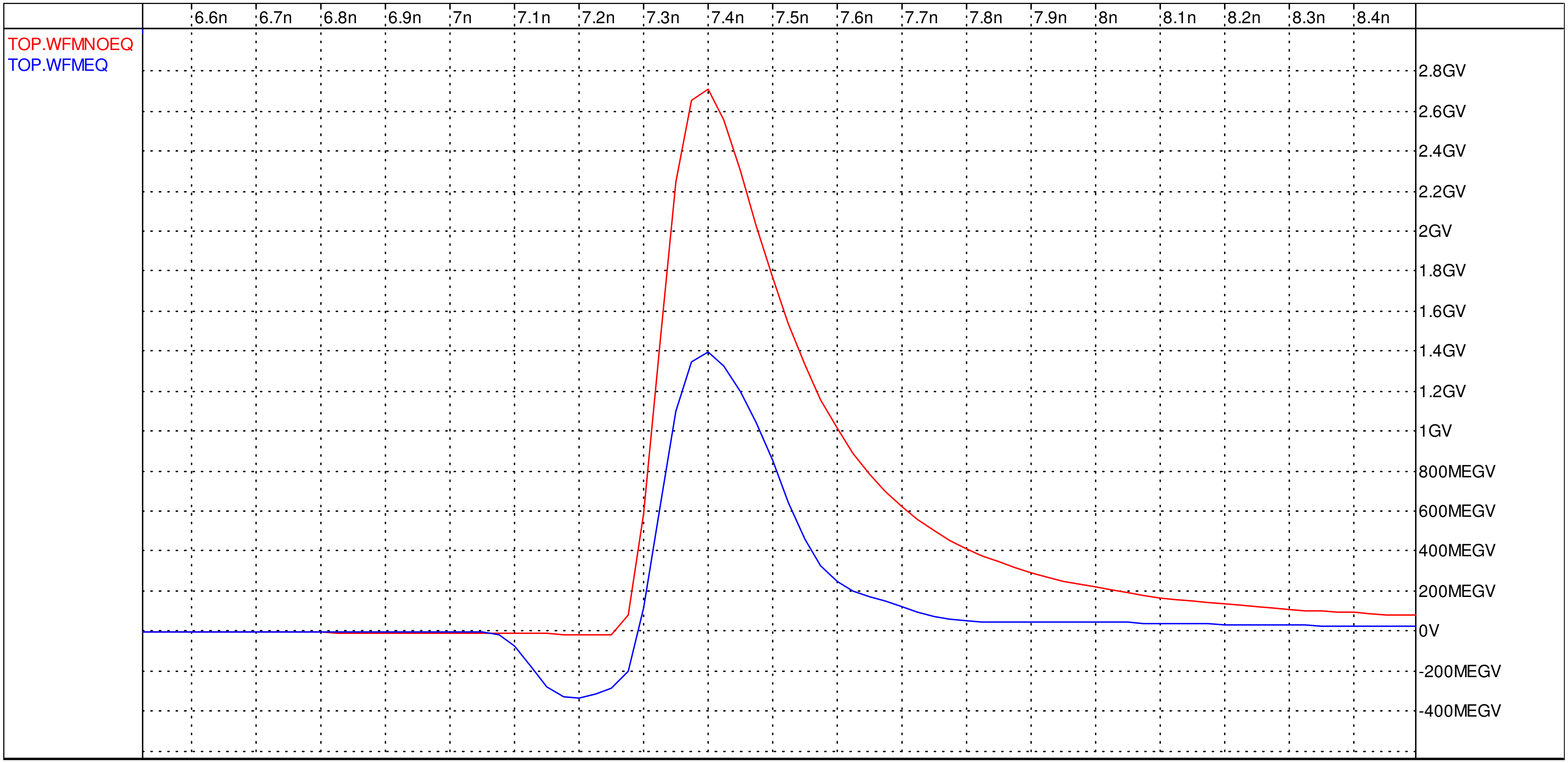
The Tx model in VHDL-AMS - cont'd

```
  -- Save the remaining response for the next block of data
  for indx in 0 to RowSize-1 loop
    tmp_dbl(indx) := tmp_dbl(indx+WaveSize);
  end loop;
  for indx in RowSize-1 to tmp_dbl'right loop
    tmp_dbl(indx) := tmp_dbl(RowSize-1);
  end loop;

  GwTime := GwTime + real(WaveSize) * SampleInterval;
  ----------------------------------------------------------------------------
  return ReturnVec;
  ----------------------------------------------------------------------------
end function AMI_getwave;
--==============================================================================
```

This code is reproduced here but is not used in the example

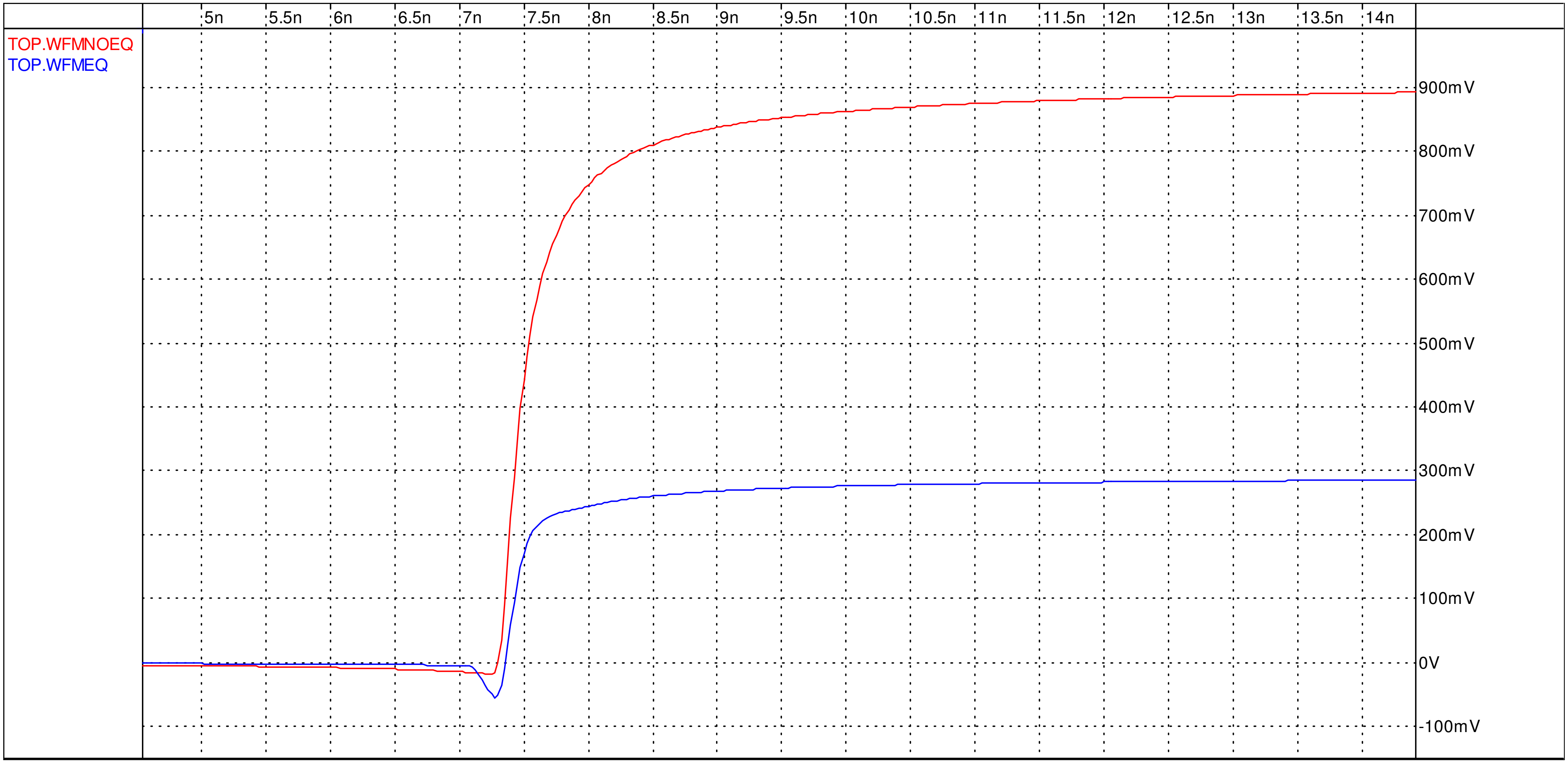
Impulse response from Tx AMI-init



Red: tap coefficients: 0 1 0 0

Blue: tap coefficients: -0.15 0.7 -0.125 -0.025

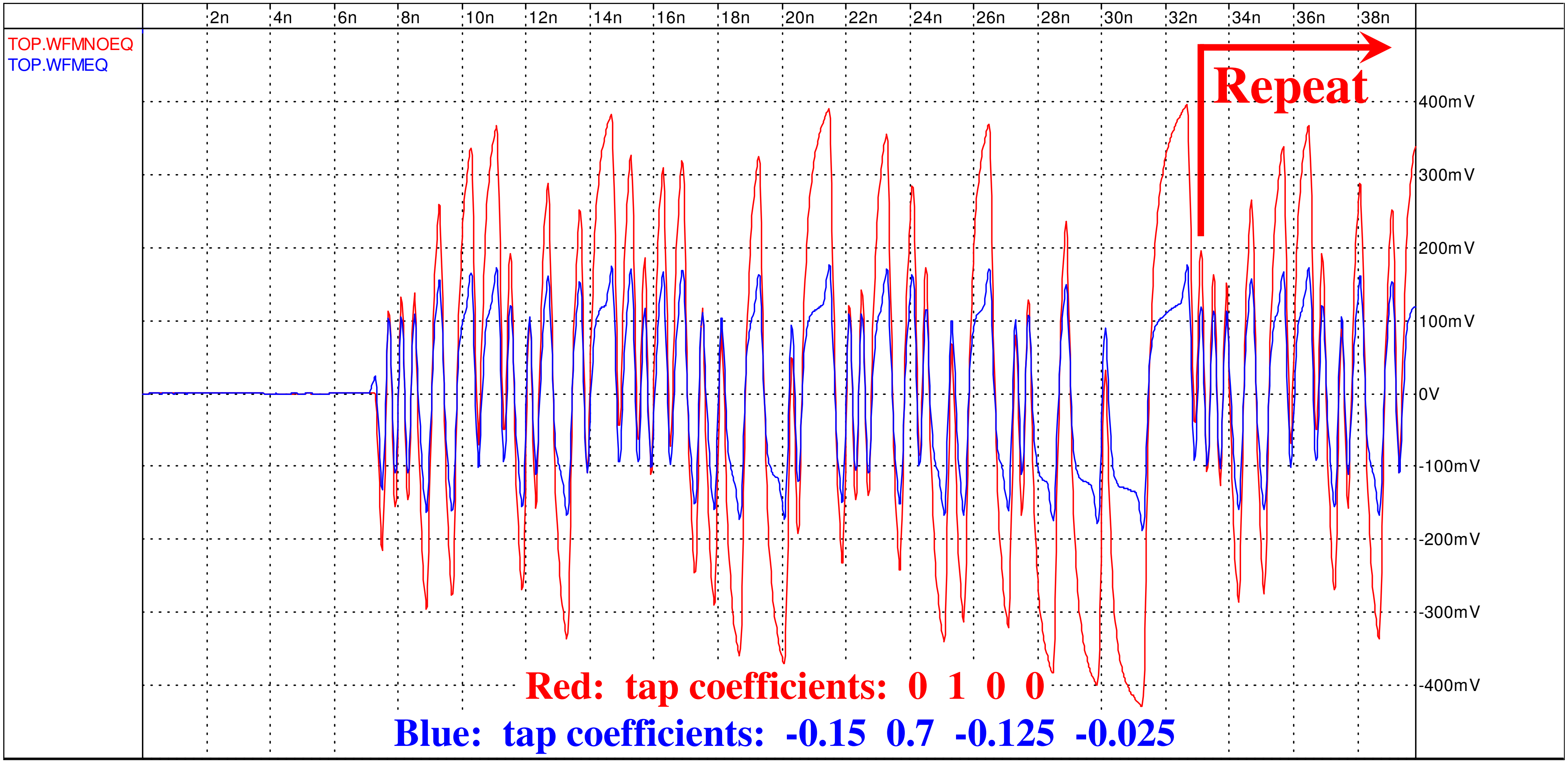
Step response from Tx AMI-init



Red: tap coefficients: 0 1 0 0

Blue: tap coefficients: -0.15 0.7 -0.125 -0.025

Rx pad waveform from Tx AMI-getwave

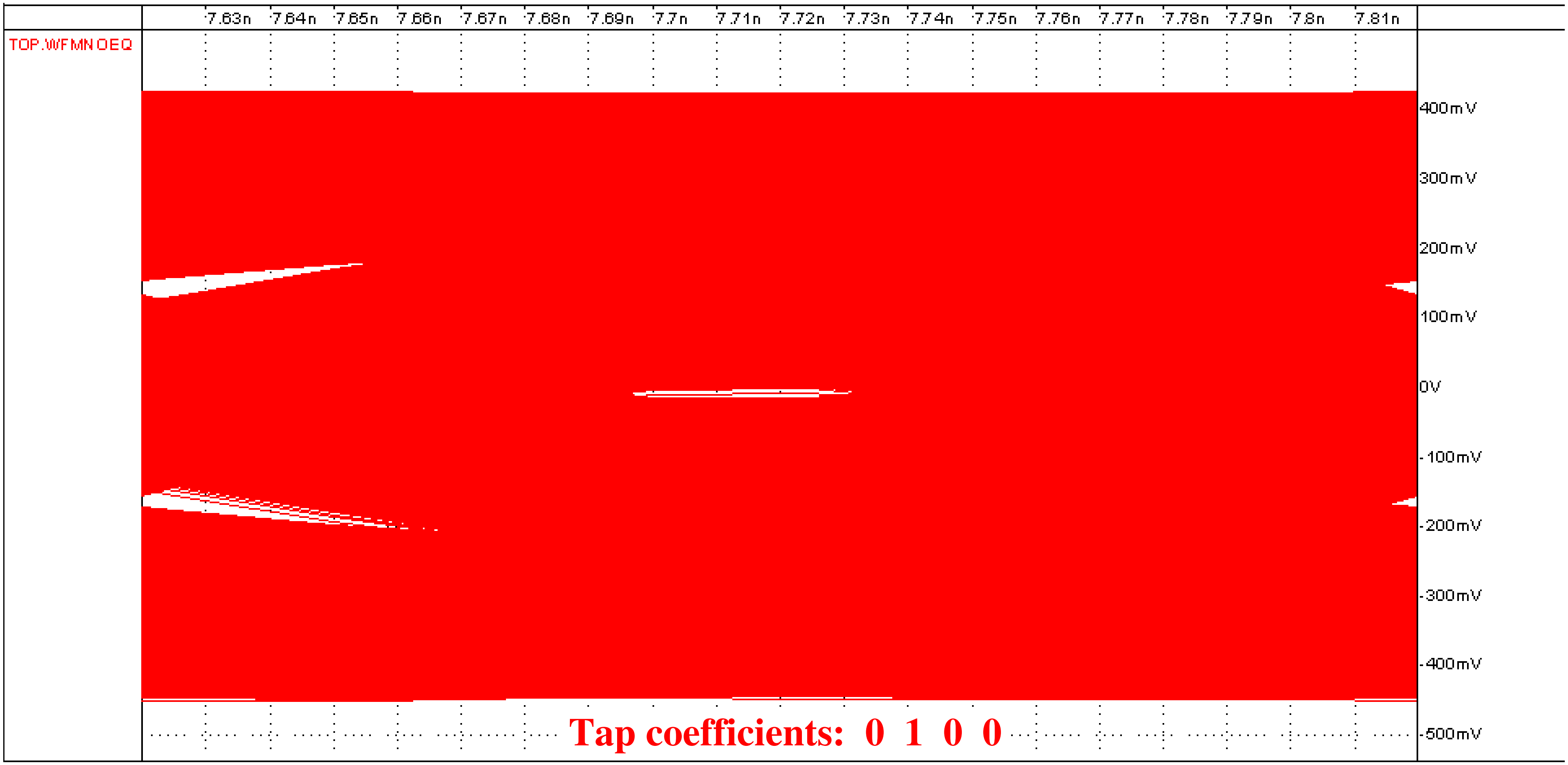


Bit time: 200 ps, Sampling time: 25 ps

Register length: 7 (128 bits)

Simulation stop time: 40 ns (more than all bits)

Rx pad eye diagram from Tx AMI-getwave

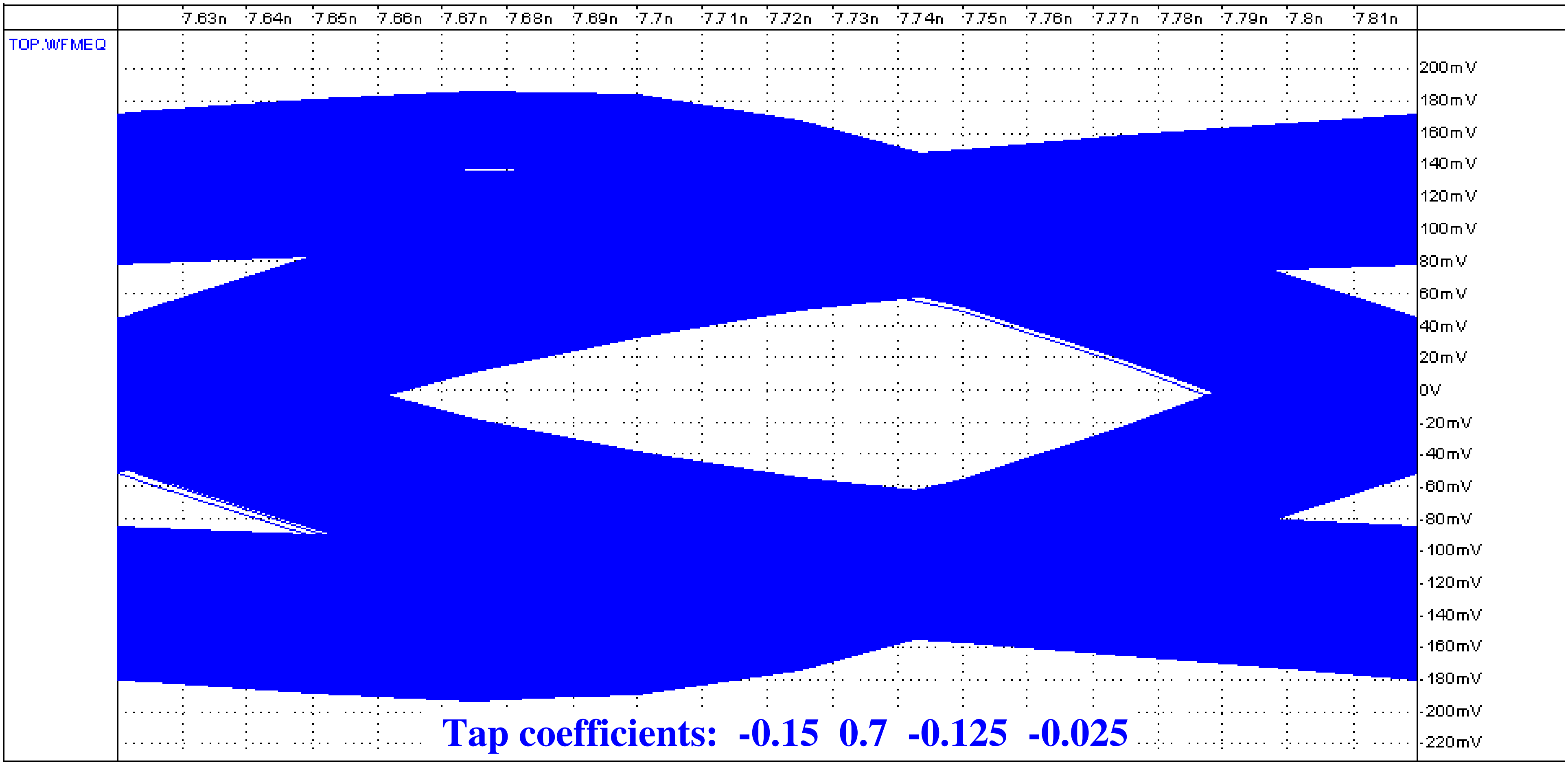


Bit time: 200 ps, Sampling time: 25 ps

Register length: 15 (32,768 bits)

Simulation stop time: 6.554 μs (all bits)

Rx pad eye diagram from Tx AMI-getwave

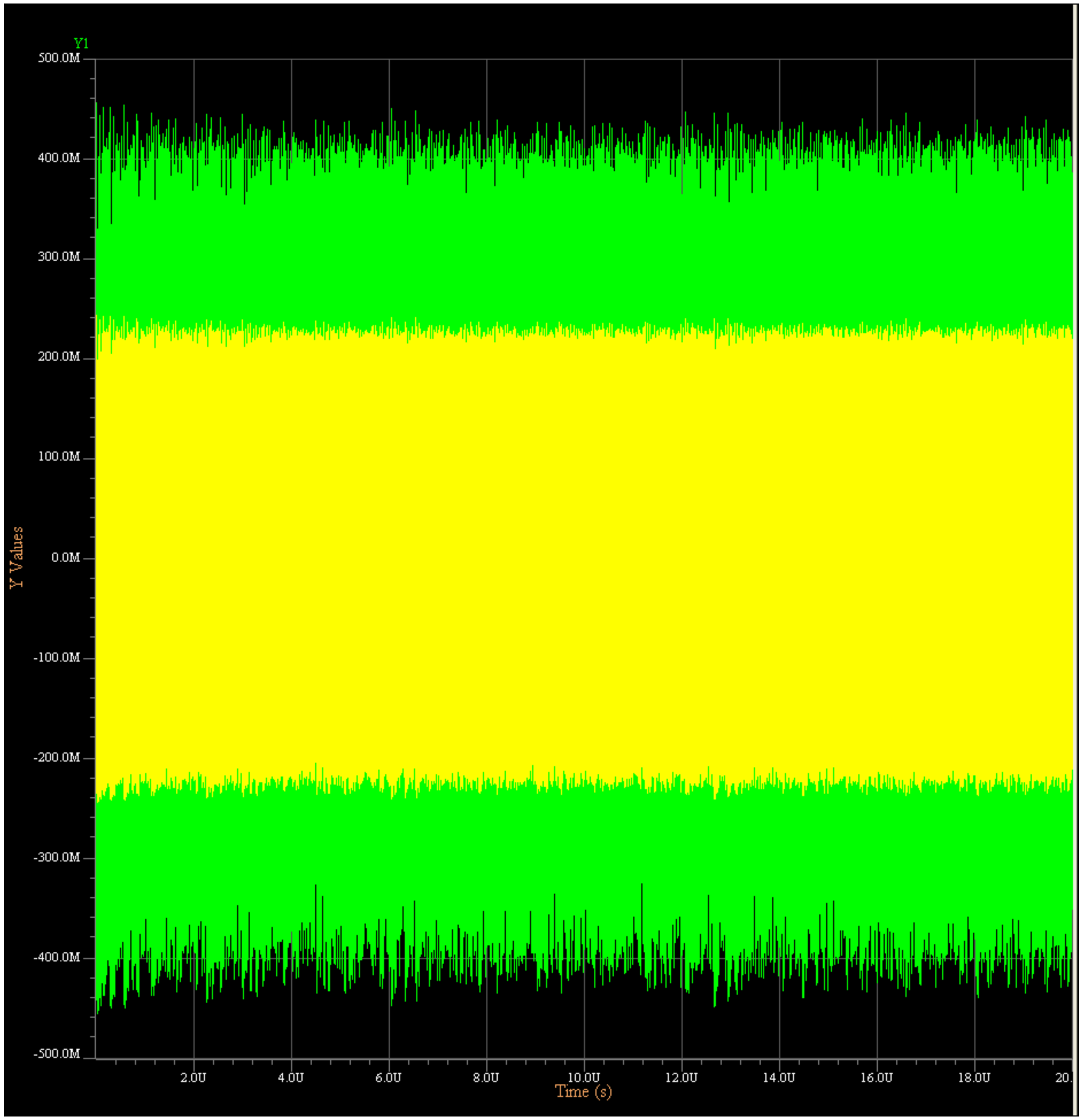


Bit time: 200 ps, Sampling time: 25 ps

Register length: 15 (32,768 bits)

Simulation stop time: 6.554 µs (all bits)

Rx pad waveform from Tx AMI-getwave



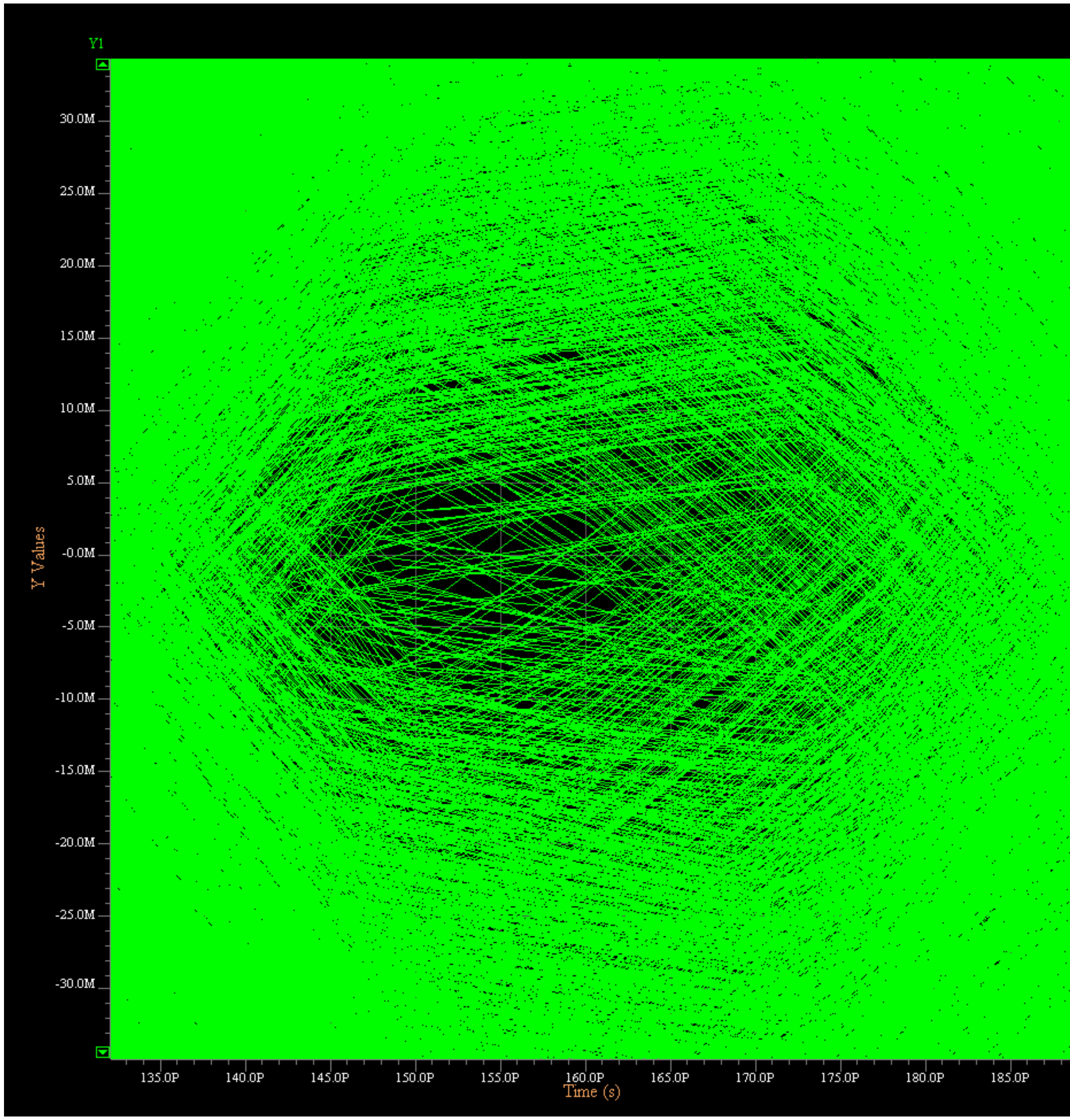
Green:
tap coefficients:
0 1 0 0

yellow:
tap coefficients:
-0.15 0.7 -0.125 -0.025

Bit time: 200 ps
Register length: 22
(4,194,304 bits)

Simulation stop time:
20 µs (100,000 bits)

Rx pad eye diagram from Tx AMI-getwave



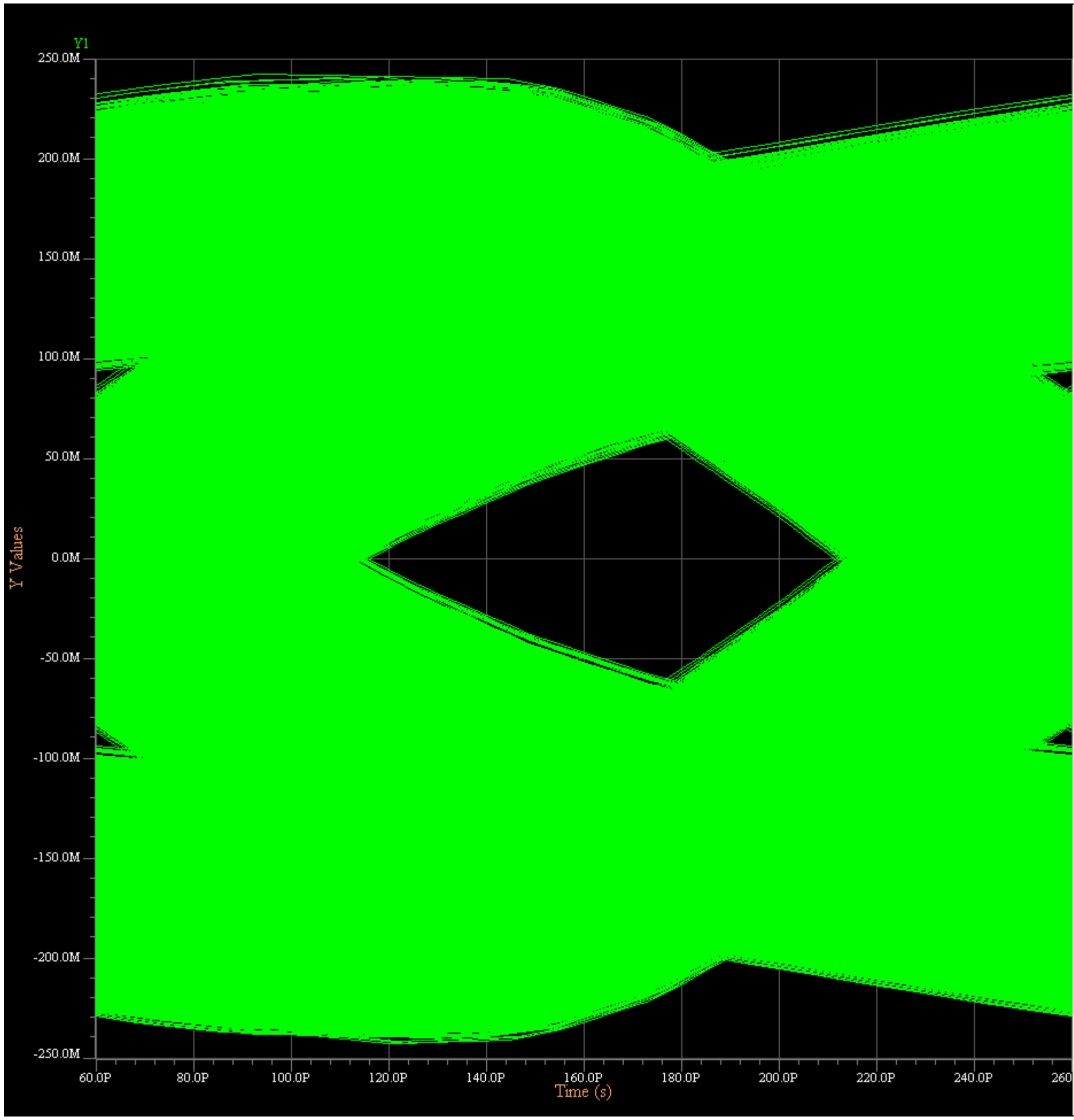
Green:
tap coefficients:
0 1 0 0

Bit time: 200 ps
Register length: 22
(4,194,304 bits)

Simulation stop time:
20 µs (100,000 bits)

Zoomed in close to the center of the eye

Rx pad eye diagram from Tx AMI-getwave



Green:
tap coefficients:
-0.15 0.7 -0.125 -0.025

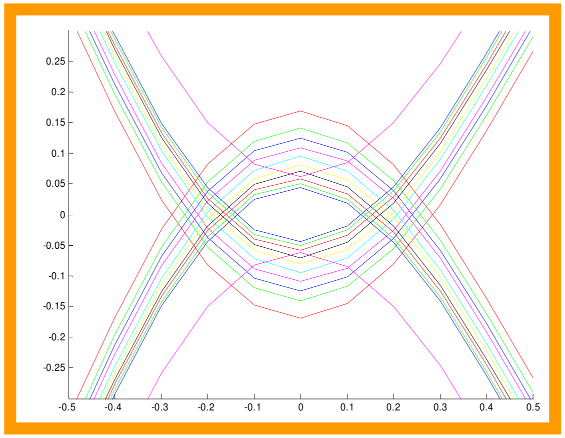
Bit time: 200 ps
Register length: 22
(4,194,304 bits)

Simulation stop time:
20 μs (100,000 bits)

Zoomed out to show the full eye diagram

IBIS-AMI with Different Languages

IBIS Summit, DesignCon, February 2008



1. **Overview: The IBIS-AMI BIRD and Toolkits**
2. **The language of IBIS-AMI models**
3. **Comments on the Tx model in C**
4. **The Tx model in VHDL-AMS**
5. **The Tx model in Matlab**
6. **Benchmarks and Conclusions**

The Tx model in Matlab

```
%%=============================================================================
function [ImpulseMatrix, StepResponse] = AMI_init(RowSize, ...
                                                  Aggressors, ...
                                                  SampleInterval, ...
                                                  BitTime, ...
                                                  TxSwing, ...
                                                  TapCoeff, ...
                                                  ImpulseMatrix)
%%=============================================================================
  TapCoeffNorm   = TapCoeff;
  Norm           = 0.0;
  Samples        = 1;
  Samp_dbl       = 0.0;

  ImpResponse    = zeros(size(ImpulseMatrix(:,2)));
  StepResponse   = zeros(size(ImpulseMatrix(:,2)));
  %%---------------------------------------------------------------------------
  %% Normalize the tap coefficients
  %%---------------------------------------------------------------------------
  for i = 1:1:size(TapCoeff,1)
    Norm = Norm + abs(TapCoeff(i,2));
  end
  for i = 1:1:size(TapCoeff,1)
    TapCoeffNorm(i,2) = TapCoeff(i,2) / Norm;
  end
  %%---------------------------------------------------------------------------
```

Note:
The parameter tree parser was not implemented in the file I/O functions of this Matlab example

The Tx model in Matlab - cont'd

```
%%-----------------------------------------------------------------------------
%% Calculate samples per bit
%%-----------------------------------------------------------------------------
Samp_dbl = BitTime / SampleInterval - 0.5;
while (Samples < Samp_dbl)
  Samples = Samples + 1;
end
%%-----------------------------------------------------------------------------
%% Calculate equalized impulse response
%%-----------------------------------------------------------------------------
for yndx = 0:1:Aggressors
  for indx = 1:1:RowSize
    ImpResponse(indx+RowSize*yndx) = TapCoeffNorm(1,2)*ImpulseMatrix(indx+RowSize*yndx,2);
    if (indx > Samples)
      ImpResponse(indx+RowSize*yndx) = ImpResponse(indx+RowSize*yndx) ...
                                 + TapCoeffNorm(2,2)*ImpulseMatrix(indx+RowSize*yndx-Samples,2);
    end
    if (indx > 2*Samples)
      ImpResponse(indx+RowSize*yndx) = ImpResponse(indx+RowSize*yndx) ...
                                 + TapCoeffNorm(3,2)*ImpulseMatrix(indx+RowSize*yndx-2*Samples,2);
    end
    if (indx > 3*Samples)
      ImpResponse(indx+RowSize*yndx) = ImpResponse(indx+RowSize*yndx) ...
                                 + TapCoeffNorm(4,2)*ImpulseMatrix(indx+RowSize*yndx-3*Samples,2);
    end
    ImpResponse(indx+RowSize*yndx) = ImpResponse(indx+RowSize*yndx) * TxSwing;
  end
end
ImpulseMatrix(:,2) = ImpResponse(:);
%%-----------------------------------------------------------------------------
```

"round to the nearest" function…

4-tap FIR filter

The Tx model in Matlab - cont'd

```
  %%--------------------------------------------------------------------------
  %% Calculate step response
  %%--------------------------------------------------------------------------
  StepResponse(1) = SampleInterval * ImpResponse(1);
  for indx = 2:1:RowSize
    StepResponse(indx) = StepResponse(indx-1) + SampleInterval * ImpResponse(indx);
  end
%%============================================================================
%% End function AMI_init
%%============================================================================
```

The Tx model in Matlab - cont'd

```
%%=============================================================================
function [ReturnVec] = AMI_getwave(RowSize, ...
                                   Aggressors, ...
                                   SampleInterval, ...
                                   BitTime, ...
                                   TxSwing, ...
                                   TapCoeff, ...
                                   ImpulseMatrix, ...
                                   StopTime, ...
                                   WaveIn)
%%=============================================================================
  WaveSize = floor(StopTime / SampleInterval);
  TempSize = RowSize + WaveSize;

[dummy,StepResponse] = AMI_init(RowSize, ...
                           Aggressors, ...
                           SampleInterval, ...
                           BitTime, ...
                           TxSwing, ...
                           TapCoeff, ...
                           ImpulseMatrix);

  Clock_indx     = 1;
  GwTime         = 0.0;
  StepSize       = 0.0;
  LastIn         = 0.0;
  ClockTimes     = [];
  ReturnVec      = zeros(TempSize,1);
  tmp_dbl        = zeros(size(ReturnVec));
  %%---------------------------------------------------------------------------
```

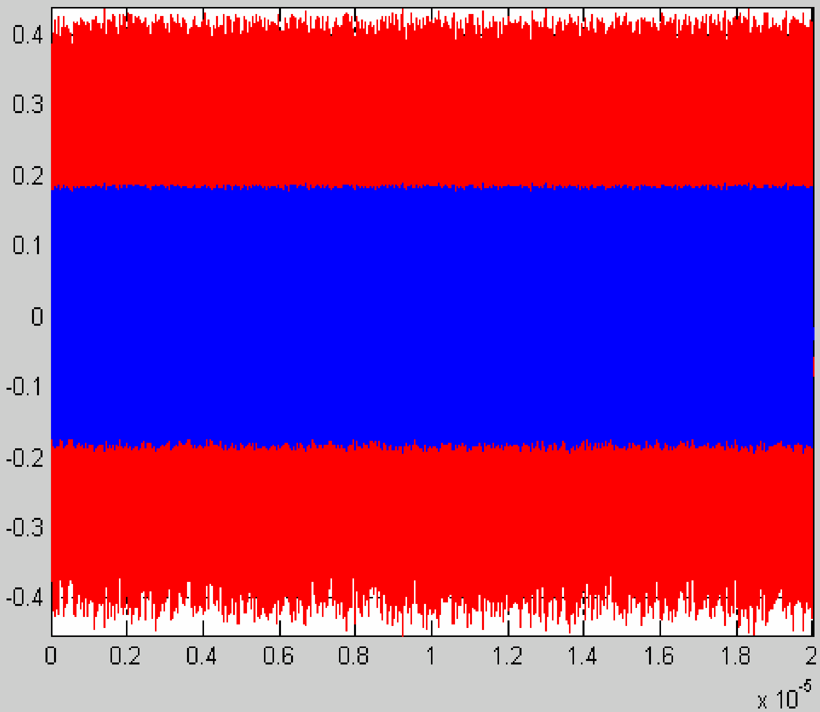
The Tx model in Matlab - cont'd

```
%%-------------------------------------------------------------------------
%% Compute the response
%%-------------------------------------------------------------------------
for indx = 1:1:WaveSize
  %% Save the time of each edge of WaveIn in ClockTimes
  if (WaveIn(indx,2)*LastIn < 0.0 )
    ClockTimes(Clock_indx) = GwTime + (indx-0.5) * SampleInterval;
    Clock_indx = Clock_indx + 1;
  end

  if (WaveIn(indx,2) ~= LastIn)
    %% Add step response
    StepSize = WaveIn(indx,2) - LastIn;
    for yndx = 0:1:RowSize-1
      ReturnVec(indx+yndx) = ReturnVec(indx+yndx) + StepSize * StepResponse(yndx+1);
    end
    for yndx = indx+RowSize:1:TempSize
      ReturnVec(yndx) = ReturnVec(yndx) + StepSize * StepResponse(RowSize);
    end
  end
  LastIn = WaveIn(indx,2);
end
%% Terminate the list of clock ticks
ClockTimes(Clock_indx) = -1.0;
%% Save the remaining response for the next block of data - not implemented
GwTime = GwTime + real(WaveSize) * SampleInterval;
%%=============================================================================
%% End function AMI_getwave
%%=============================================================================
```

using a step response as an input, this makes a convolution function

Rx pad waveform from Tx AMI-getwave



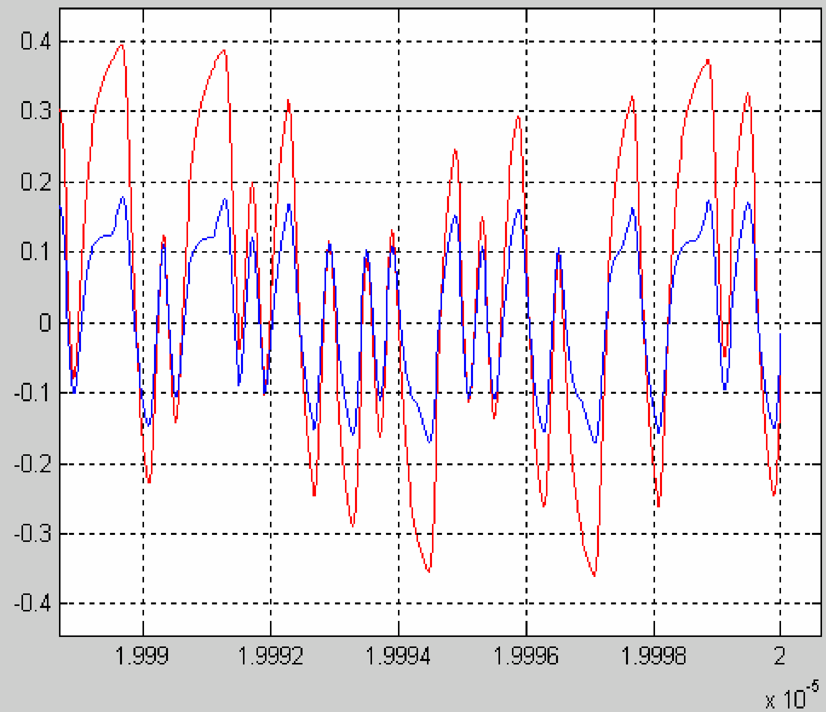
Red: tap coefficients: 0 1 0 0

Blue: tap coefficients: -0.15 0.7 -0.125 -0.025

Bit time: 200 ps

Register length: 22 (4,194,304 bits)

Simulation stop time: 20 µs (100,000 bits)



Tx AMI-init in Matlab - done properly

```
%%==============================================================================
function ImpulseMatrix = AMI_init(SampleInterval, ...
                                  BitTime, ...
                                  TxSwing, ...
                                  TapCoeff, ...
                                  ImpulseMatrix)
%%==============================================================================
  TapCoeffNorm = TapCoeff;
  Norm         = 0.0;
  Samples      = 1;
  Aggressors   = max(0,size(ImpulseMatrix,2)-2);
  %%----------------------------------------------------
  %% Normalize the tap coefficients
  Norm = sum(abs(TapCoeff(:,2)));
  TapCoeffNorm(:,2) = TapCoeff(:,2) / Norm;
  %%--------------------------------------------------------------------------
  %% Calculate samples per bit
  Samples = round(BitTime/SampleInterval);
  %%----------------------------------------------------
  %% Calculate equalized impulse response
  b = zeros(Samples,size(TapCoeffNorm,1));
  b(1,:) = TapCoeffNorm(:,2)';
  b = reshape(b,1,[]);
  ImpulseMatrix(:,2:Aggressors+2) = TxSwing * filter(b,1,ImpulseMatrix(:,2:Aggressors+2));
%%==============================================================================
%% End function AMI_init
%%==============================================================================
```

The "vector notation" can eliminate all or most FOR loops, executes faster and reads better

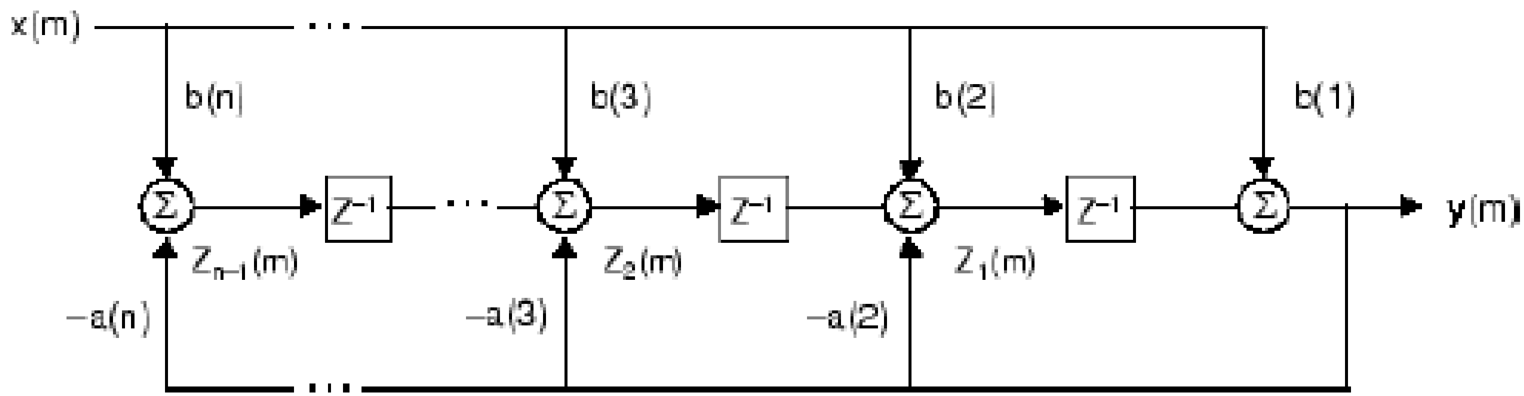
Built-in functions are more convenient, and execute faster

The *reshape* and *filter* functions in Matlab

```
A =
        1       4       7       10
        2       5       8       11
        3       6       9       12

B = reshape(A,2,[])

B =
        1       3       5       7       9      11
        2       4       6       8      10      12
```



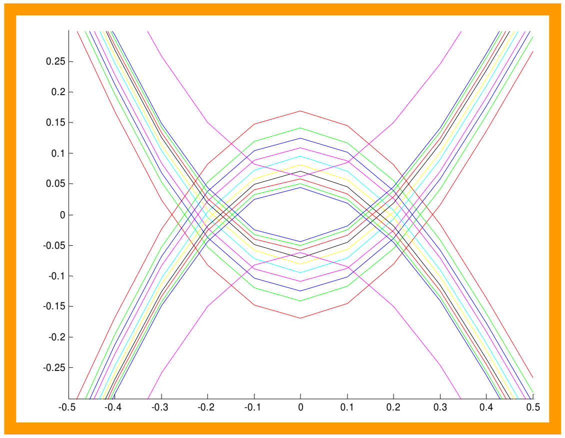
$$Y(z) = \frac{b(1) + b(2)z^{-1} + \ldots + b(nb+1)z^{-nb}}{1 + a(2)z^{-1} + \ldots + a(na+1)z^{-na}} X(z)$$

Tx AMI-getwave in Matlab - done properly

```
%%===============================================================================
function ReturnVec = AMI_getwave(SampleInterval, ...
                                 BitTime, ...
                                 TxSwing, ...
                                 TapCoeff, ...
                                 ImpulseMatrix, ...
                                 StopTime, ...
                                 WaveIn)
%%===============================================================================
  WfmSize         = floor(StopTime / SampleInterval);
  ReturnSize      = size(ImpulseMatrix,1) + WfmSize;
  ReturnVec       = zeros(ReturnSize,1);
  ImpulseResponse = AMI_init(SampleInterval, ...
                             BitTime, ...
                             TxSwing, ...
                             TapCoeff, ...
                             ImpulseMatrix);
  %%-----------------------------------------------------------------------------
  %% Save the time of each edge of WaveIn crossing 0 volts
  ClockTimes = (WaveIn(find(diff(sign(WaveIn(1:WfmSize,2))))  ,1) ...
             +  WaveIn(find(diff(sign(WaveIn(1:WfmSize,2))))+1,1) ) / 2;
  %% And terminate the list of clock ticks
  ClockTimes(length(ClockTimes)+1) = -1.0;
  %%-----------------------------------------------------------------------------
  %% Compute the response
  ReturnVec = SampleInterval * conv(WaveIn(:,2),ImpulseResponse(:,2));
%%===============================================================================
%% End function AMI_getwave
%%===============================================================================
```

The built-in convolution function "conv" reduced multiple FOR loops into this single line

IBIS-AMI with Different Languages



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Benchmarks

PRBS register length:	22
Sampling time:	25 ps
Bit time:	200 ps
Stop time:	20 μs

Original code in ANSI C:	10.0 sec
Matlab (properly coded):	3.5 sec
Matlab (C clone):	14:00.0 sec
VHDL-AMS (simulator #1):	23:33.0 sec
VHDL-AMS (simulator #2):	1:15:45.0 sec

Comments on the benchmarks

- The benchmarks were not obtained from rigorous coding practices
  - neither the original C code and its "clones" were optimized
  - the 2nd version of the Matlab code was developed to show the efficiency and power of the Matlab syntax
- No research has been done yet to find the reasons for the poor performance of the VHDL-AMS code
  - the code is implemented in digital functions, so the analog solver was ***not*** involved in their execution
  - much better performance was expected
  - VHDL-AMS tools compile the source code which could theoretically be as fast as compiled C code

Conclusions

- ANSI C is the most inconvenient language, but fast
  - nice function libraries would help a great deal
  - but most computer science "stuff" will remain in the code
    - malloc, free, pointer of pointers, etc…
- VHDL-AMS somewhat better
  - most computer science "stuff" is not needed
  - but could use nice function libraries
  - some language limitations exist
    - functions can return one item only
    - no control over argument passing into functions (byRef / byValue)
    - arrays can't be resized, etc…
- Matlab
  - the most friendly and efficient language of these three
  - its execution speed is competitive with ANSI C

The source code will be available

The source code of the VHDL-AMS and Matlab examples will be posted on the IBIS web site shortly after the Summit

Have fun experimenting with them!

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