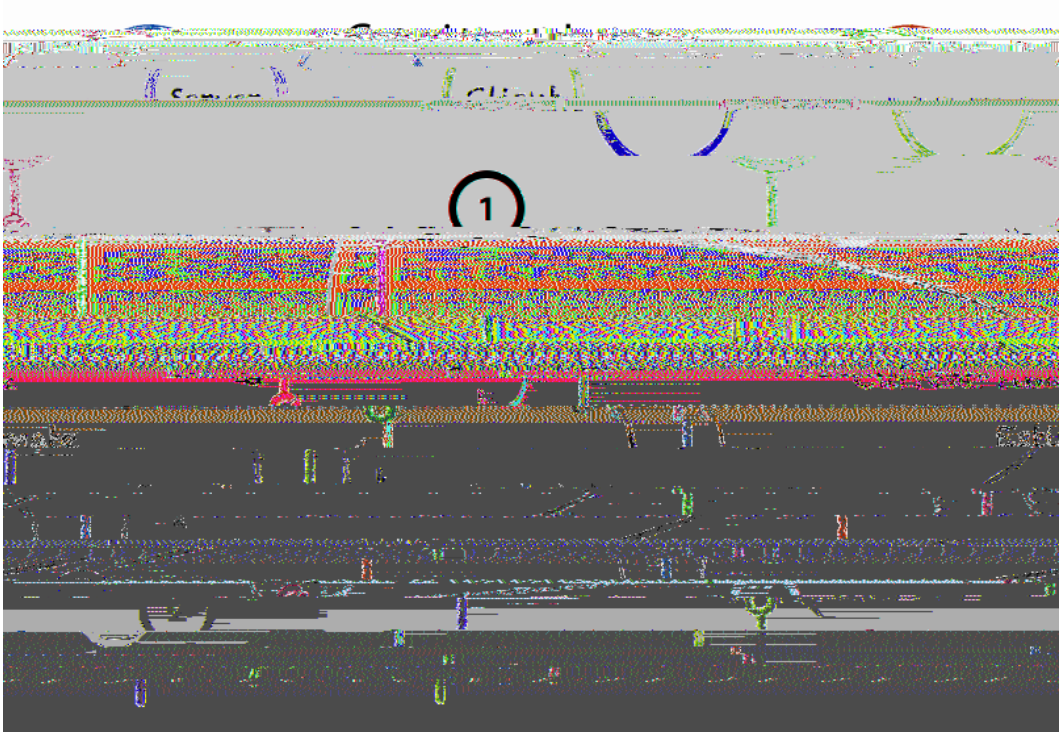
TABLE OF CONTENTS

LOGICAL TIME SYNCHRONIZATION IN DISTRIBUTED NETWORKS WITH VOLATILE LATENCY

Previous Work

CRISTIAN'S ALGORITHM



Cristian's Algorithm assumes latency is relatively consistent, so that dividing the total round-trip message time, t_r, in half will result in an accurate estimate of network latency.

It does not scale well:

Accuracy declines with increased latency volatility:

It is not naturally distributed:

It's a one-way protocol:

Very accurate in certain conditions:

Strong resistance to network volatility:

Adaptable to distributed networks:

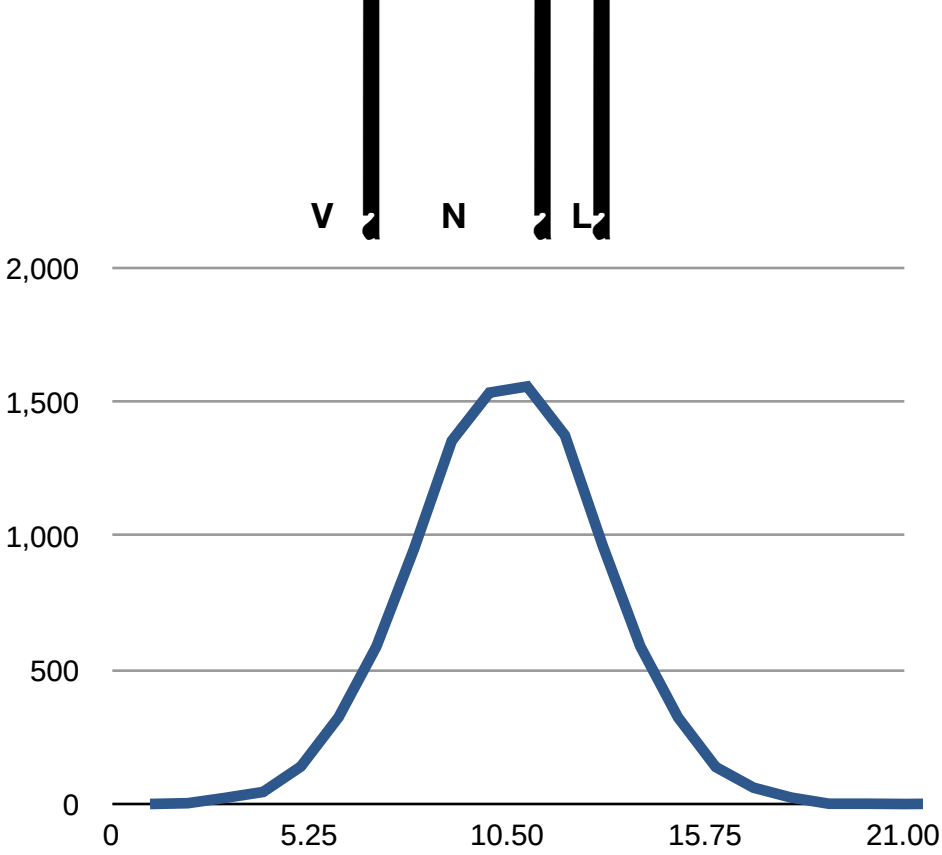
Adaptable to changes in overall network latency behavior:

Works well in both low and high latency volatility:

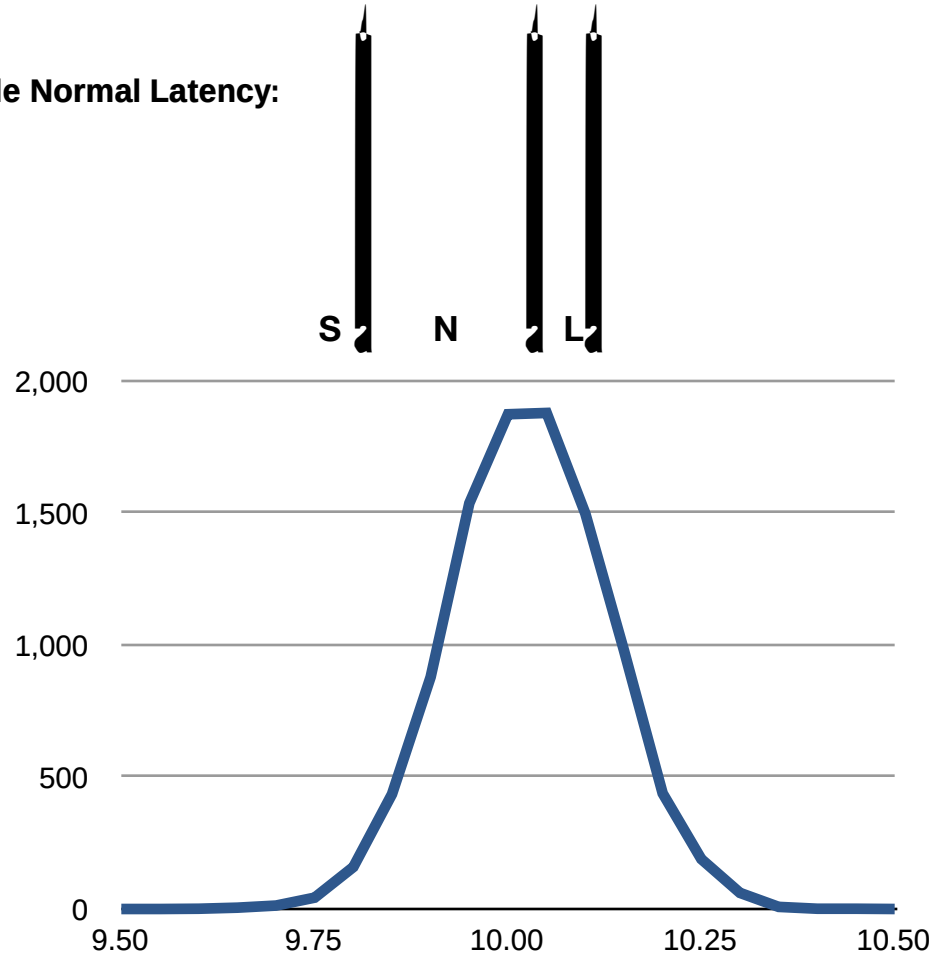
Simulation Results

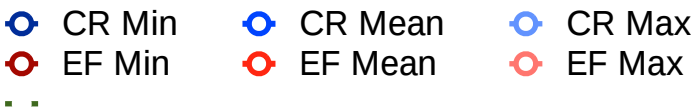
IMPLEMENTATION

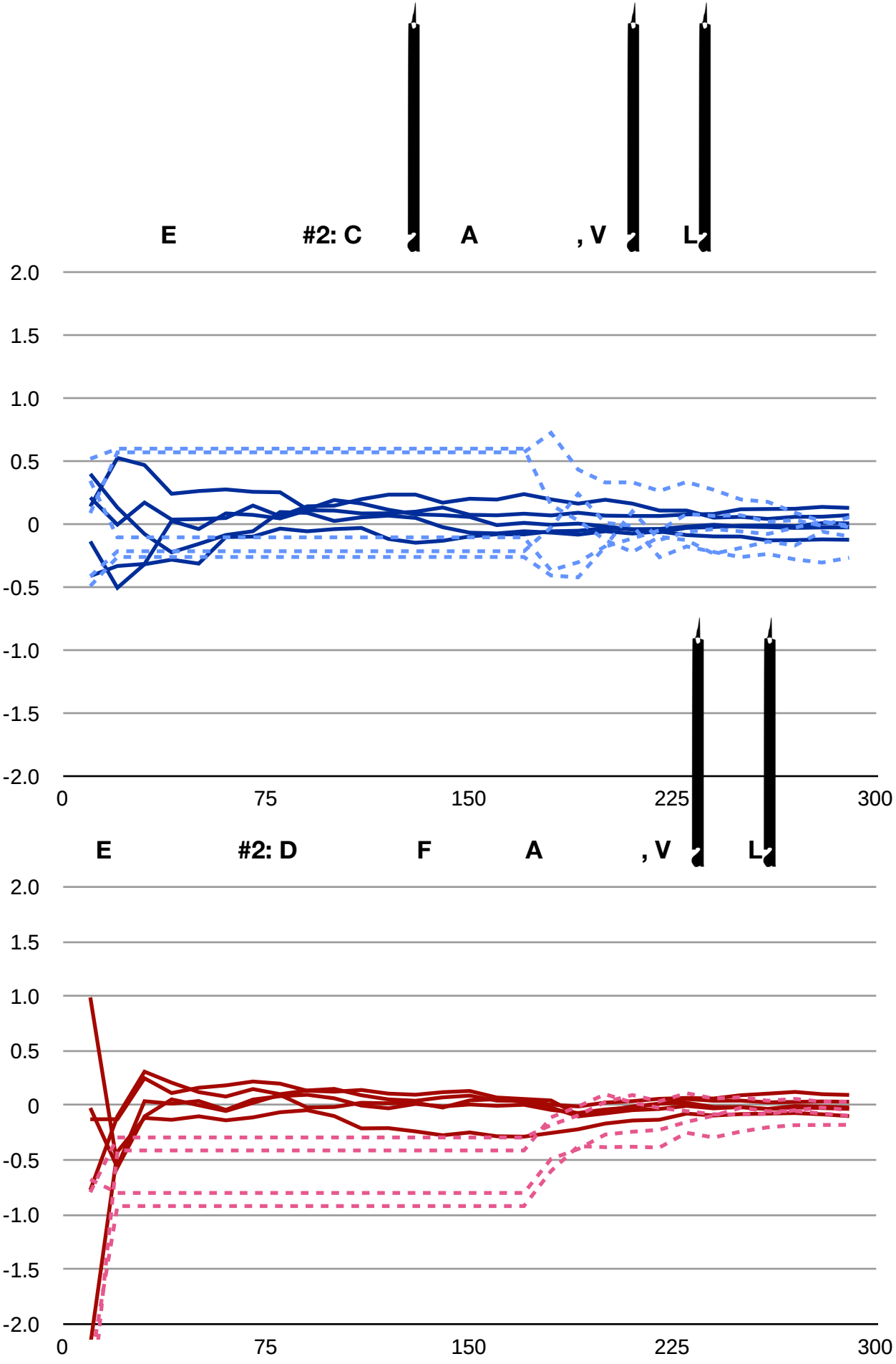
“Long-Tail” Normal Latency:

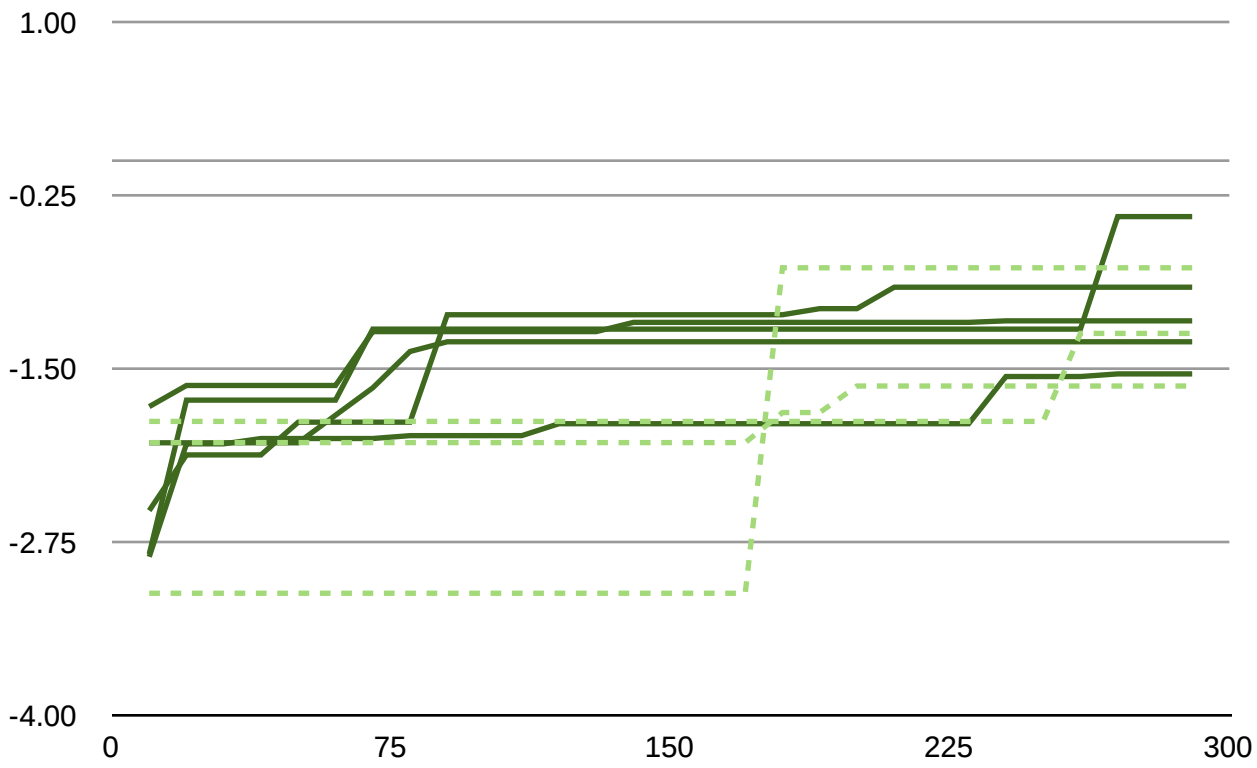


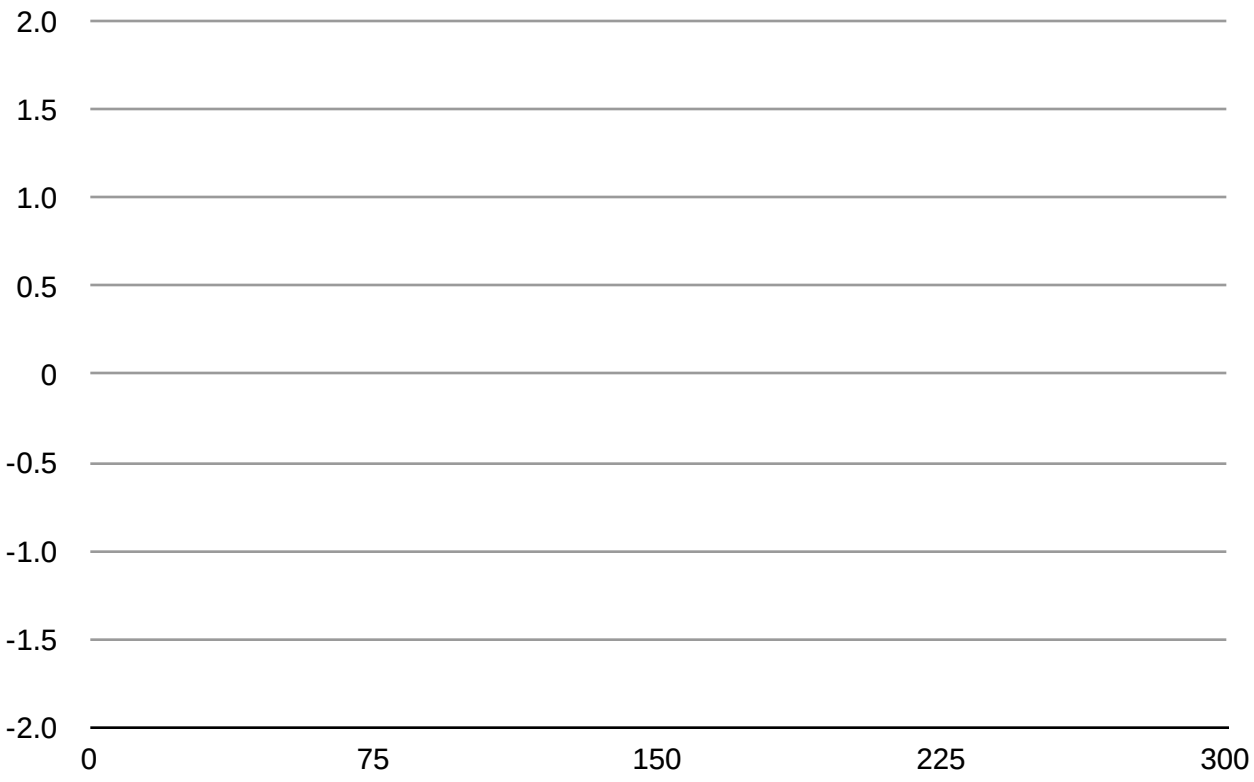
Stable Normal Latency:

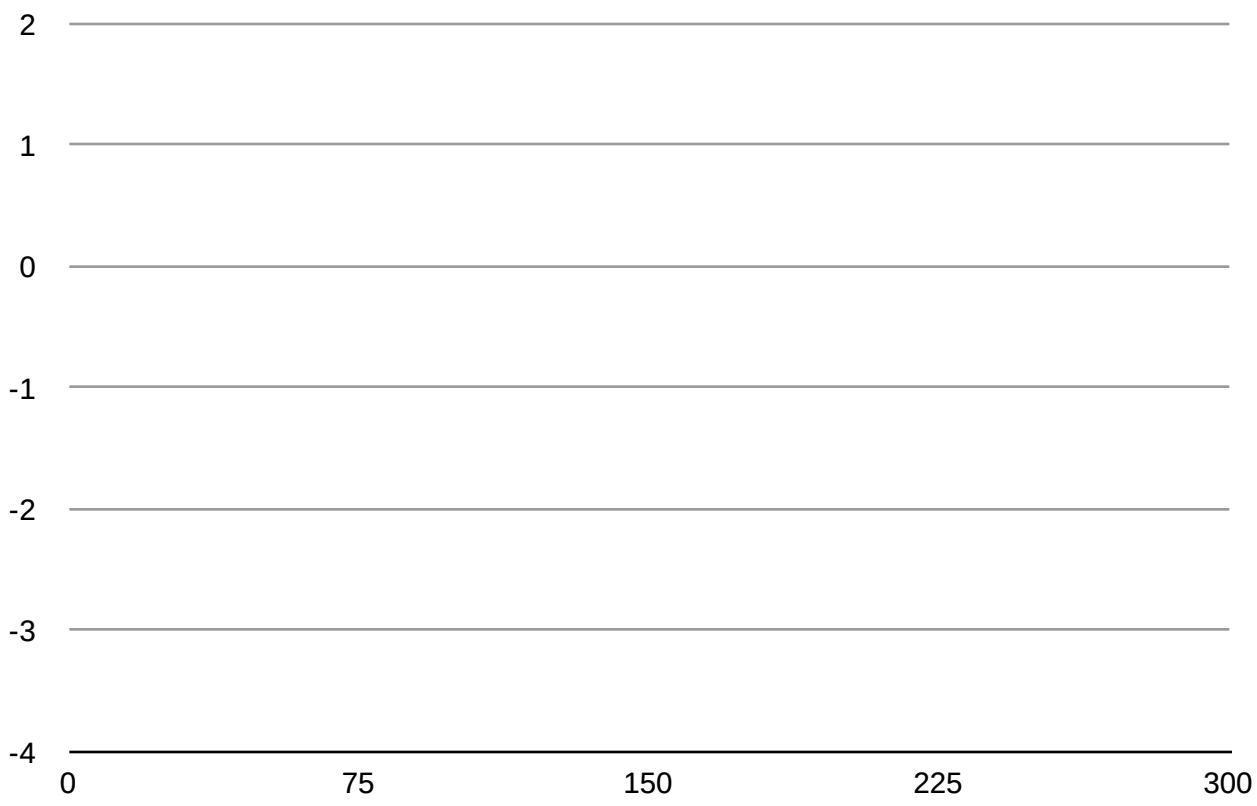



CR Min
CR Mean
CR Max
EF Min
EF Mean
EF Max


E #2: C A , V L
2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
0
75
150
225
300
E #2: D F A , V L
2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
0
75
150
225
300


1.00
-0.25
-1.50
-2.75
-4.00
0
75
150
225
300


2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
0
75
150
225
300


2
1
0
-1
-2
-3
-4
0
75
150
225
300

Hardware Results

IMPLEMENTATION

Future Work

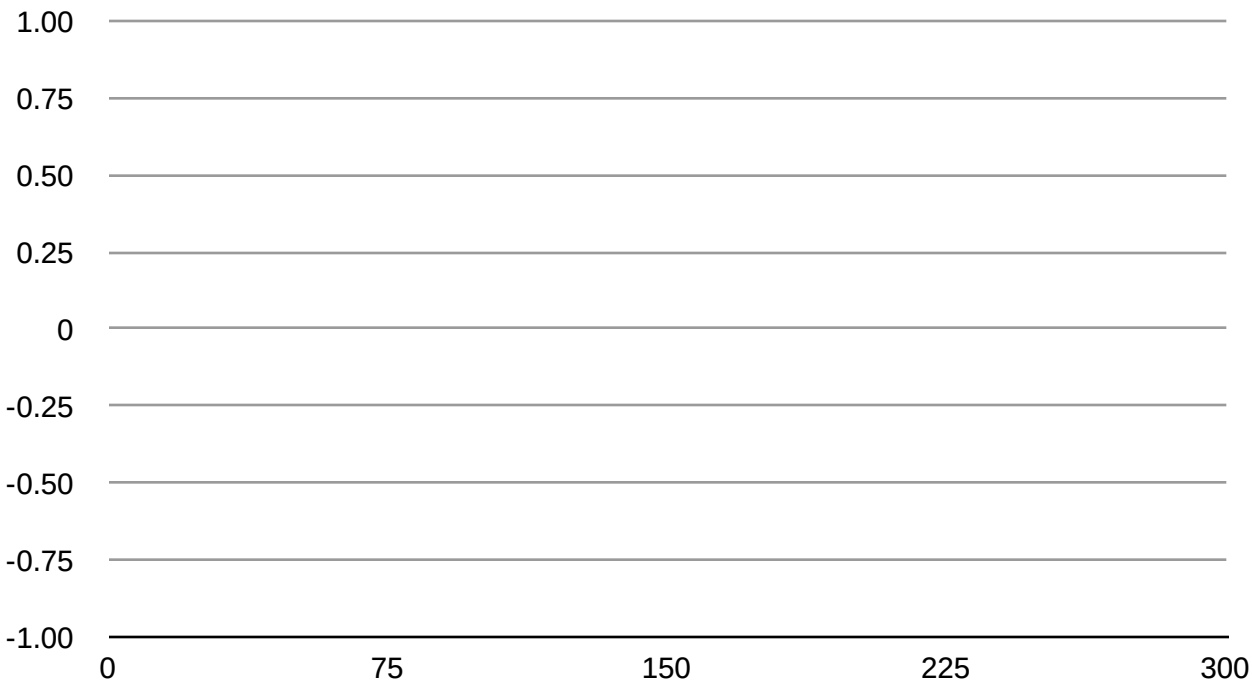
ALGORITHM IMPROVEMENTS

References

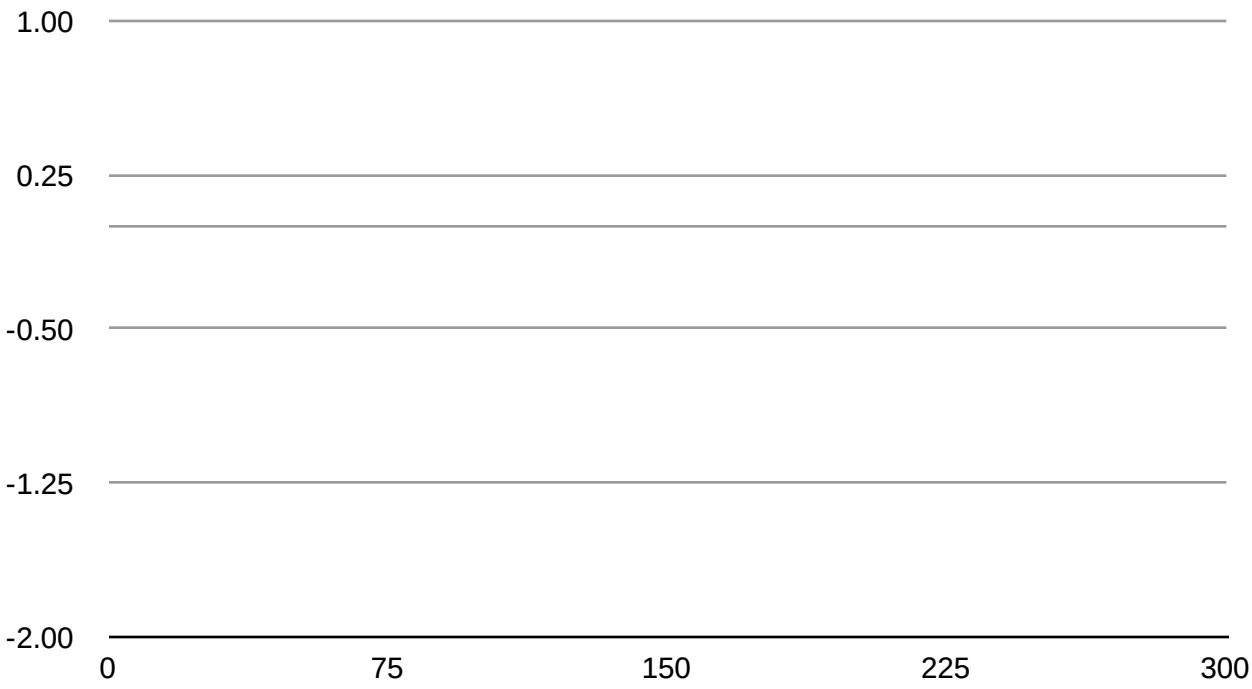
Appendix A: Simulation Results

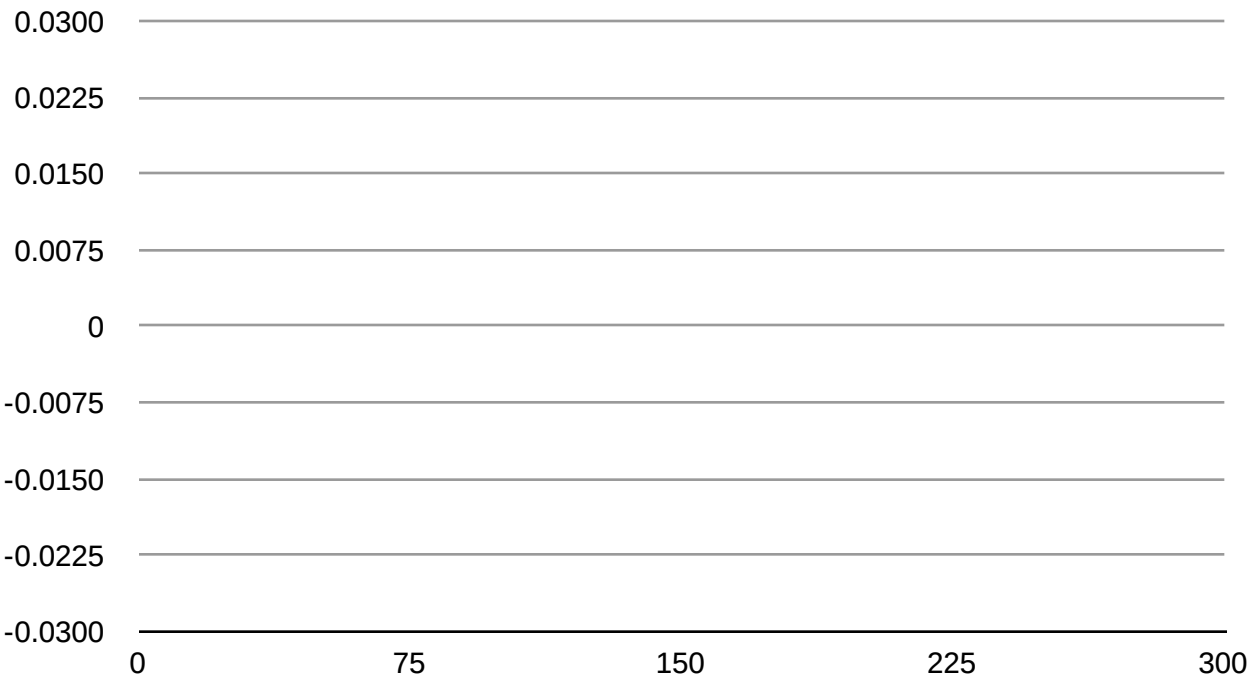
EXPERIMENT #1: BASE TIME RECORD SET

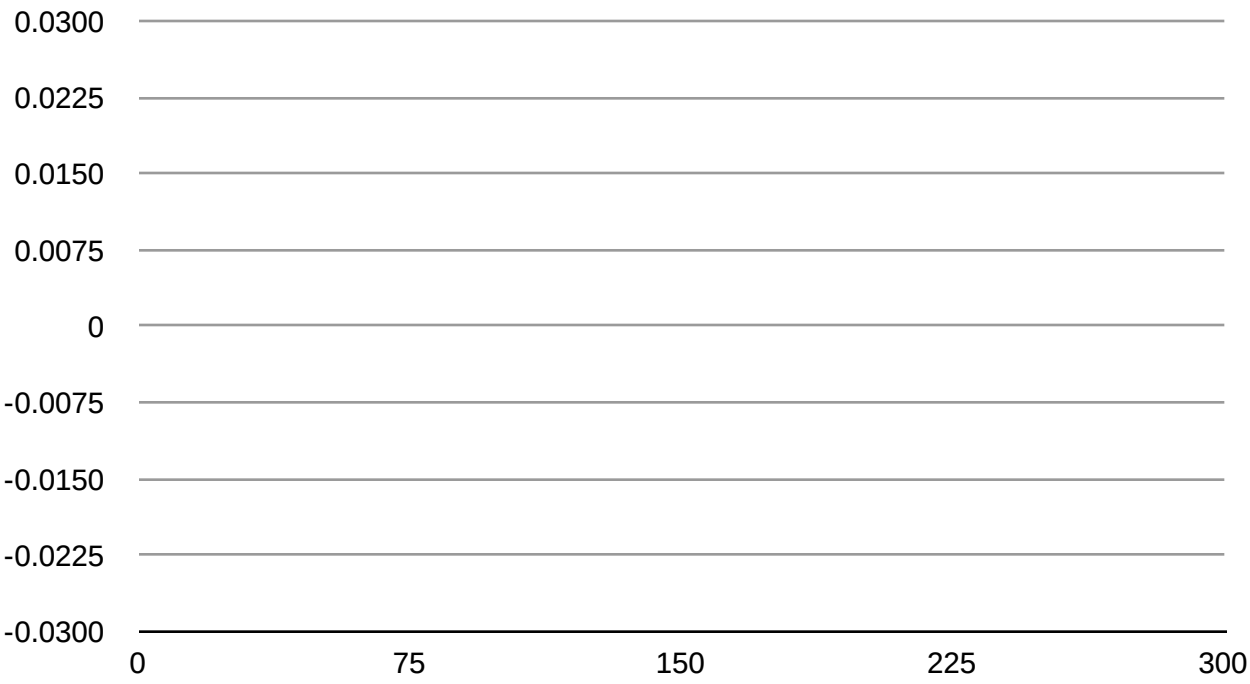
( ) + (+1)∗( )


1.00
0.75
0.50
0.25
0
-0.25
-0.50
-0.75
-1.00
0
75
150
225
300


1.00
0.25
-0.50
-1.25
-2.00

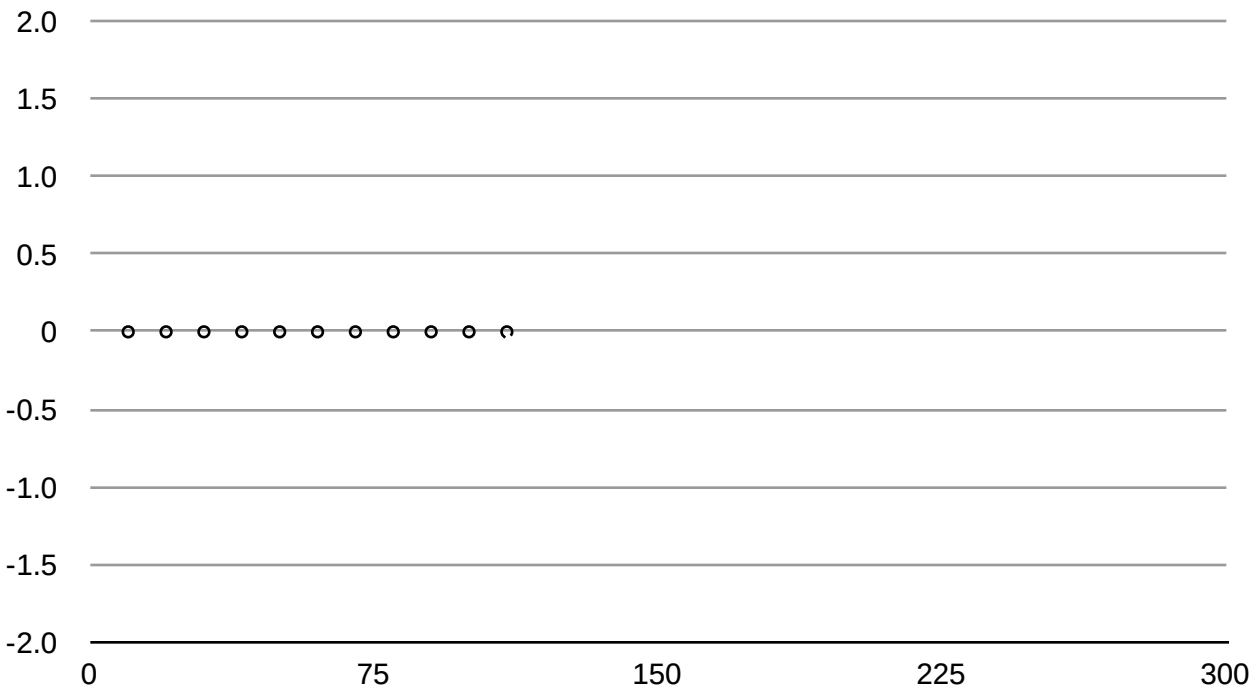

1.00
0.25
-0.50
-1.25
-2.00
0
75
150
225
300

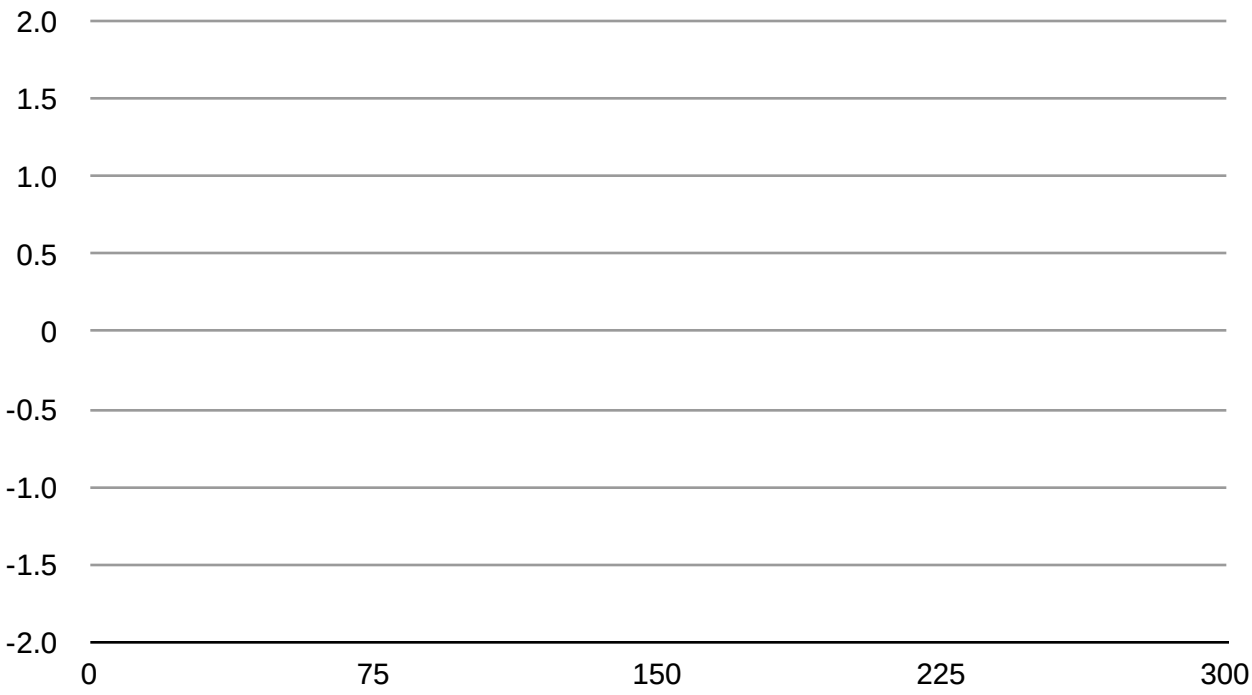

0.0300
0.0225
0.0150
0.0075
0
-0.0075
-0.0150
-0.0225
-0.0300
0
75
150
225
300

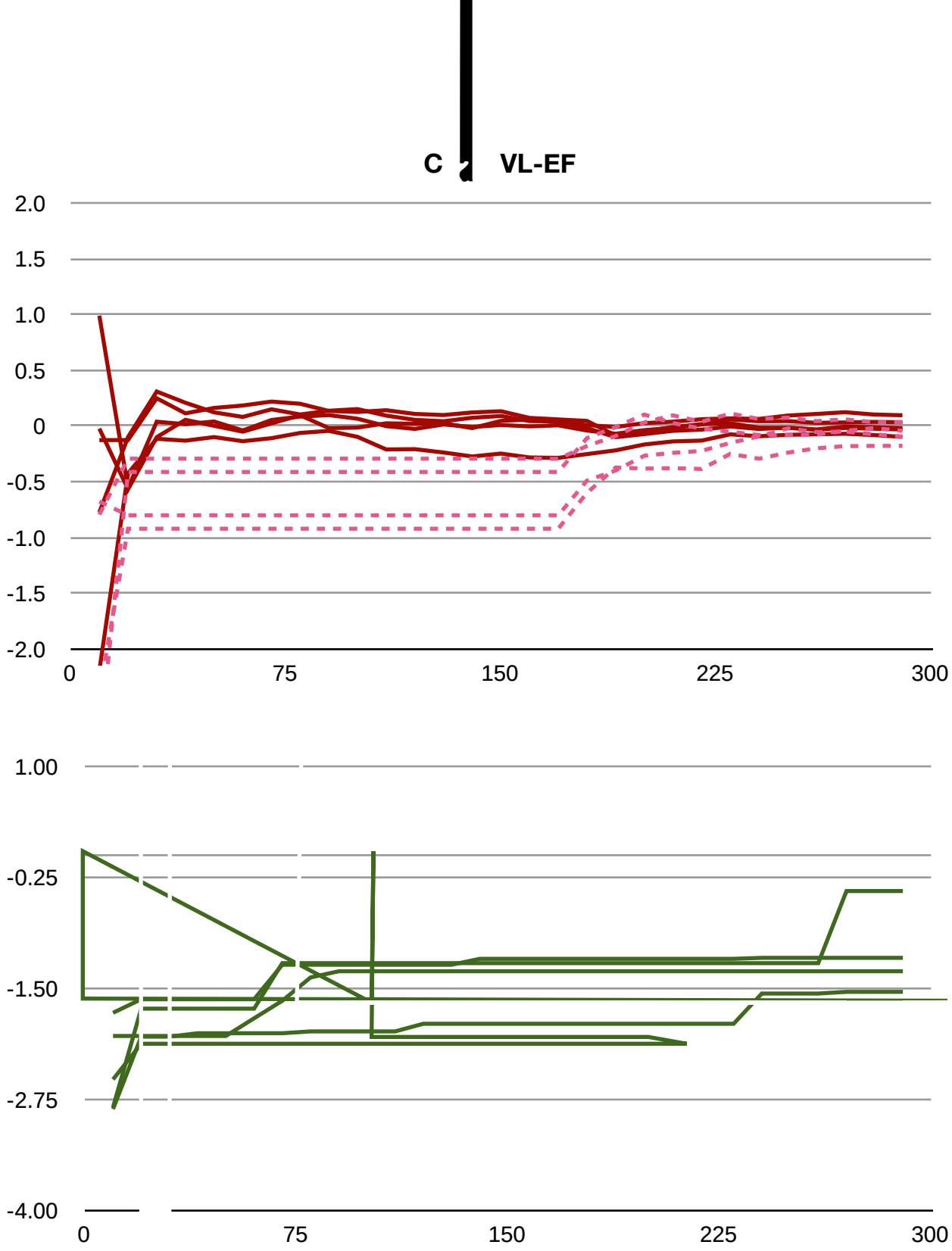

0.0300
0.0225
0.0150
0.0075
0
-0.0075
-0.0150
-0.0225
-0.0300
0
75
150
225
300

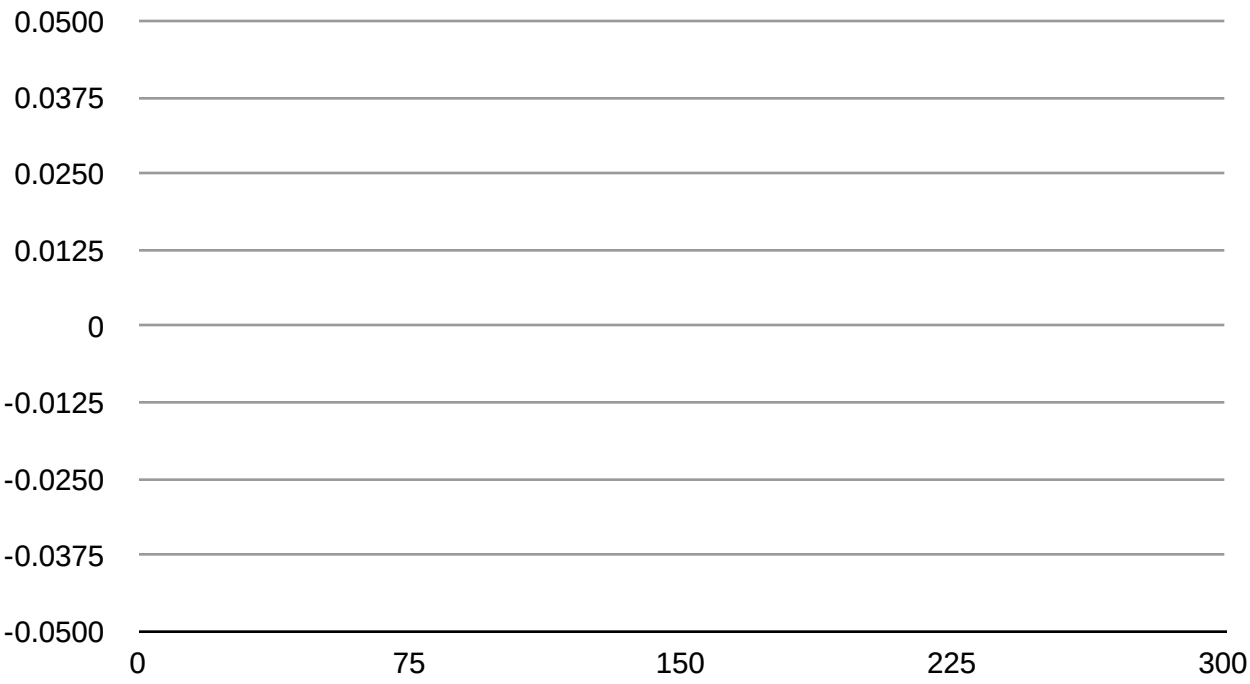
EXPERIMENT #2: CLIENT DISCONNECT

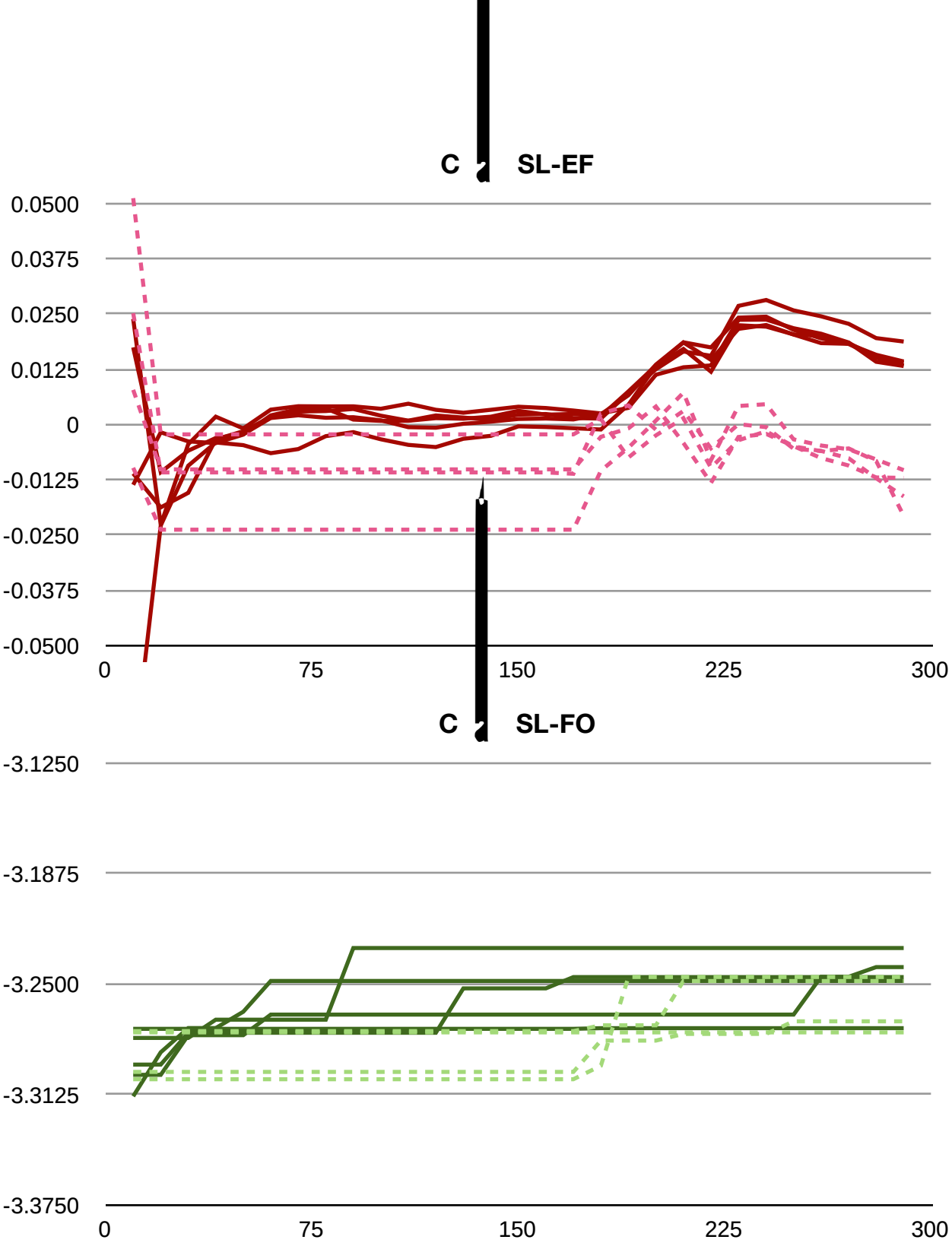
Tests:


2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
0
75
150
225
300

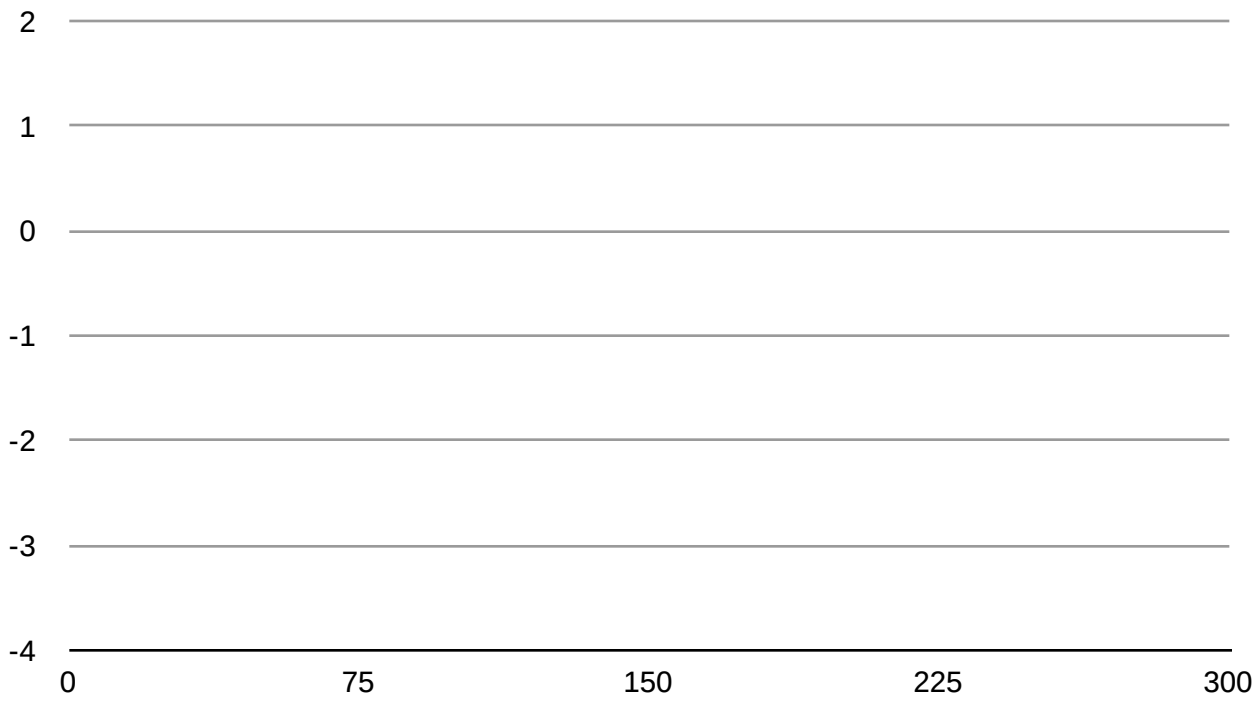

2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
0
75
150
225
300

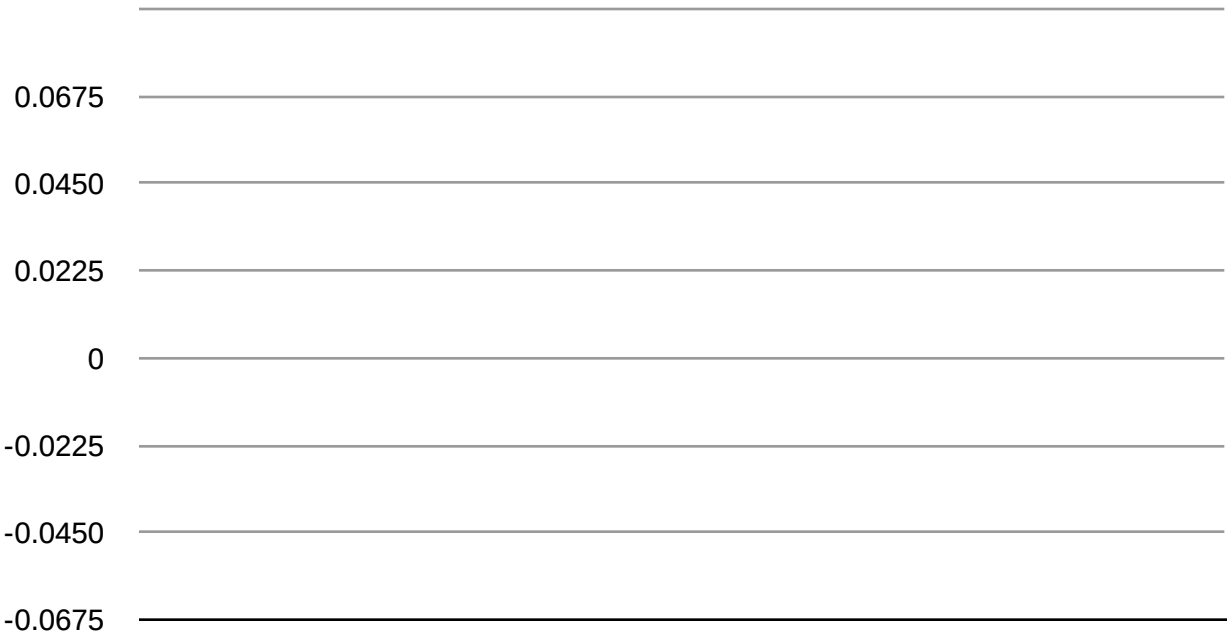

C
VL-EF
2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
0
75
150
225
300
1.00
-0.25
-1.50
-2.75
-4.00
0
75
150
225
300


0.0500
0.0375
0.0250
0.0125
0
-0.0125
-0.0250
-0.0375
-0.0500
0
75
150
225
300


C
SL-EF
0.0500
0.0375
0.0250
0.0125
0
-0.0125
-0.0250
-0.0375
-0.0500
0
75
150
225
300
C
SL-FO
-3.1250
-3.1875
-3.2500
-3.3125
-3.3750
0
75
150
225
300

EXPERIMENT #3: SERVER DISCONNECT


2
1
0
-1
-2
-3
-4
0
75
150
225
300


0.0675
0.0450
0.0225
0
-0.0225
-0.0450
-0.0675

Appendix B: Simulation Implementation

MRFollowerNode Class

MRFollowerNode.h

```
//
//                .
//
//
//                                  2/21/13.
//            ( ) 2013                  .                    .
//

#       "              . "
#       "            . "
#       "                    . "
```

```
#           -

          (                    )(              *        ,              )



          (     ,     ,        )        *
          (     ;       ,        )

#           -
+ (  )
+ (  )                                    (                    )
(        )
- (  )                                (                    )
(        )

#           -
- (    )                                (                    *)
- (    )               (                    *)

#           -
- (                      *)
- (                      *)             (          )

#           -
- (             )                              (
```

```
#          –
        (     ,      ,          )
        (     ,      ,          )            *

#          –
        (     ,      ,                ,          )
```

```
!   !
                                        (              *       ,
    )
!   !       !


!   !                   (          , 1)
!   !
!   !                                  0
!   !
!
!
```

return

```
– (                 *)
!            ((                           *)     .
                  .                             ).
– (                 *)
!            ((                           *)     .                    ).
– (                  )
!                 .               .             +     .                 *
(    .                            + 1)
– (                  )
!                 .          .
#             –
– (     )
!
– (     )           (     )
!                  (     )
!    !           (           !           )
!    !        !
!    !        !
!    !        !        (           )
!    !        !      !          .
!    !        !      !           .
(    .                          )  // +      .                 )
!    !        !
!    !        !      !          .
!    !        !
!    !
!
– (     )                        (                )
(                )
!         .
!
!                        (          )(         /       )
!
!    !              ("(%  )                        (%  )              .  ",      .
                ,      .           .               )
!    !           (                *                  .          )
!    !        !
                                .           .                                  .
!    !
!
!
//!           (        ,
```

```
//!  !           ()
//!  !          (         0 &&     .       )             ((      -1),       ,
     )
//!   )
!
!                          (      ,       ,      ,
!    !                 .
!     )


- (    )

!       .


#            -

- (    )                     (             )

!       .
!
!            (        ,
!    !            .
!     )


#            -

- (    )            (             *)

!       (!          )
!
!       (!     .                              )
!    !            .
!


- (    )                (                   *)

!                         (
```

–

()

(, ,) *
(,

– ( ) (*)

```
!    !
!
!
!       (          0.0)
!    !                0.0
!
!                                       (     /          )
!
```

```
#             –                 (          )

                                   (          )

– (     )

!          32             (      32   )     .
!         (      32      0              ++)
               32                        –
               32           4                (          ) +
```

MRTimeRecord Class

MRTimeRecord.h

```
//
//                .
//
//
//                                2/21/13.
//            ( ) 2013             .                    .
//

#                  /          .



         (                            )(            *     ,
      )
                  (                            )(            *     ,
      )


#            -


         (        ,       ,        )                          //
+
         (        ,       ,        )                             //
         (        ,       ,        )                //

         (        ,     ,        )       *               //
         (        ;       ,        )
```

```
#            -
+ (   )                            (     )
(              )
+ (   )                            (     )
(              )
+ (   )                             (     )

#            -
- (          *)
- (          *)


#            -

               (          ,                                 )
!                                              ,
!                                           ,
!                                           ;
!


          (         ,       ,         )             *
          (         ;       ;         )             *
          (         ;       ;         )             *
          (         ;       ;         )             *
          (         ;       )
          (         ,       )

#            -
+ (   )
+ (   )                      (                               )
               (             )                  (          )
- (   )                (                               )
               (             )                  (          )
- (   )                (                               )
(     )                                 (             )
(         )

#            -
- (          *)
- (          *)
```

MRTimeRecord.m

```
//
//               .
//
//
//                                  2/21/13.
//           ( ) 2013                .                    .
//

#       "            . "


                        ()
```

```
          *
!         *
                *


         (         ,       ,          )
         (         ,       ,          )
         (         ,       ,          )
         (         ,       ,          )
```

```
#            –

+ (  )

!


+ (  )                              (                          )
             (                        )

!


– (  )


       (    )
!   !
!   !
!   !
!   !


– (
```

! (* ,
)
! ! (! .)

```
!          (                  !     )


- (        *)



- (              )

!      (                )
!   !               -
!          0.0


- (              )

!      (                        )
!   !               -
!          0.0
```

–

( )
(. .

(. .

(. .

(. .
0))))

()

(, ,) *
(, ,) *
(, ,) *
(, ,) *

–

+ (

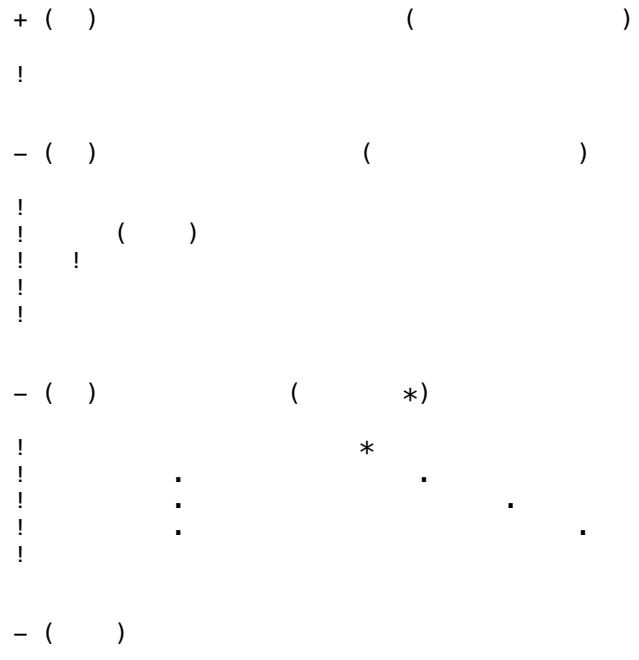
MRTimeUpdateMessage Class

MRTimeUpdateMessage.h

```
//
//                     .
//
//
//                                 2/2 /13.
//            ( ) 2013                 .                    .
//

#       "                . "



          (          ,       ,          )
          (          ,       ,         )
          (          ,       ,         )
          (          ,       )

+ (  )                      (             )
– (  )                  (             )

– (    )                             (              )
```

MRTimeUpdateMessage.m

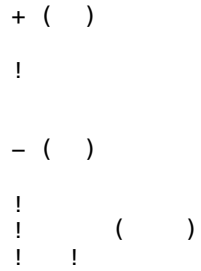
```
//
//                     .
//
//
//                                 2/2 /13.
//            ( ) 2013                 .                    .
//

#       "                    . "
#       "                   . "


                                 ()

          (          ,       ,          )
          (          ,       ,          )




– (  )

!
!      (    )
!   !                       0.0
!   !                             0.0
!   !
!
!
```

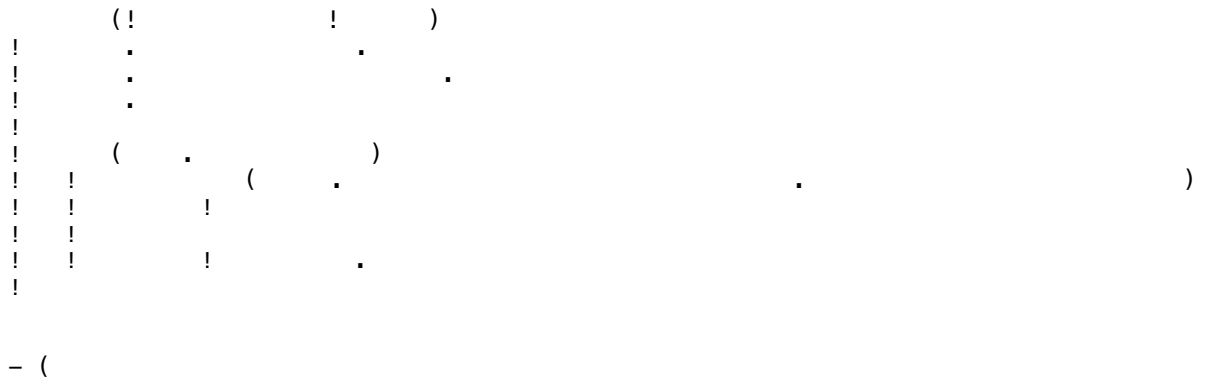


MRNetworkMessage Class

MRNetworkMessage.h

```
//
//                  .
//
//
//                                  11/1 /12.
//            ( ) 2012                .                  .
//

#                  /          .
```





MRCristianTimeServerNode Class

MRCristianTimeServerNode.h

```
//
//                          .
//                         _
//
//                                3/1 /13.
//            ( ) 2013              .                  .
//

#       "             . "
#       "                  . "


          (         ,       ,         )
```

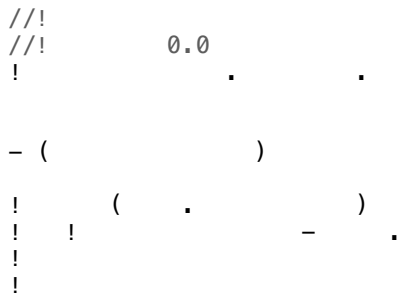
MRCristianTimeClientNode Class

MRCristianTimeClientNode.h

```
//
//                          .
//                         _
//
//                                3/1 /13.
//            ( ) 2013                .                   .
//

#       "              . "
#       "                    . "
#       "             . "


          (      ,       ,          )              *
          (      ,       ,          )              *
          (      ,       ,          )
          (      ,       ,          )
          (      ,       ,          )
          (      ,       ,          )
          (      ,       ,          )
          (      ,       ,          )
          (      ,       ,           )
          (      ,       ,                   ,         )

+ (  )                          (              )
- (  )                          (              )

+ (  )             (         *)                     (              )
- (  )             (         *)                     (              )

- (    )                              (         *)
- (    )               (         *)

#           -
- (    )                          (              )
```

MRCristianTimeClientNode.m

```
//
//                          .
//                         _
//
//                                3/1 /13.
//            ( ) 2013                .                   .
//

#       "                        . "
#       "                    . "


                                  ()

          (      ,       ,          )              *
          (      ,       ,          )              *
          (      ,       ,          )
```



```
#              –

– (     )                        (                )

!        .
!
!             (         ,
!    !               .
!    !
!     )
```

MRNetworkNode Class

MRNetworkNode.h

```
//
//                    .
//
//
```

```
!


+ (  )             (          *)

!


– (  )             (          *)

!
!      (    )
!   !                    ++
!   !
!   !
!   !                                          (
                  "   .    .% ",                    ,                              )
!
!


– (          *)

!                                      " %          "%  " ",
            ,    .



– (    )             (                *)                    (          *)

//!               (    .             ,
!   !
                                          .
//!  )


– (    )                (                *)

//!               (    .             ,
//! !              ( "(% )                  % ",    .    ,       )
//!  )
```

MRNetworkDirectory Class

MRNetworkDirectory.h

```
//
//                    .
//
//
//                                  11/1 /12.
//            ( ) 2012                  .                    .
//

#                   /          .
#       "               . "
#       "                  . "
#       "                      . "


+ (                     *)

          (          ,       ,          )

          (          ,       ,          )
          (          ,       ,           )
          (          ,       ,           )

– (     )

– (   )              (               *)

– (     )             (                  *)                     (          *)
              (          *)
– (     )              (                  *)               (              *)
         (               *)
```

MRNetworkDirectory.m

```
//
//                    .
//
//
//                                  11/1 /12.
//            ( ) 2012                  .                    .
//

#       "                    . "
#       "                       . "


                                ()
!                   *
!


          (          ,       ,           )
          (          ,       ,           )                *
          (          ,       ,           )                     *

– (     )              (               )
```

– ( ) (*)

*

+ (*)

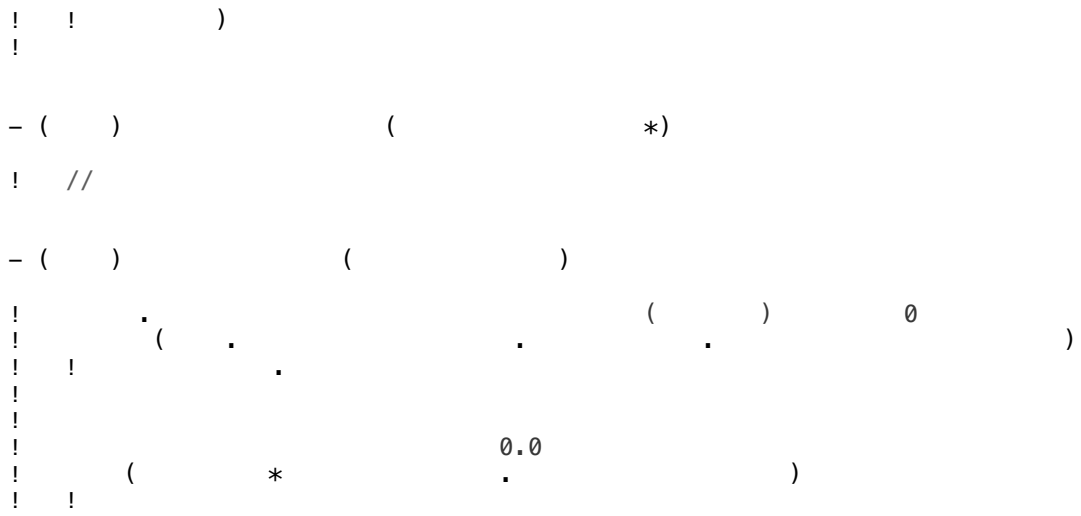
! (!)
! !
!

– ( )

( )

– ( )

!
!
! 10
! 1.0
!



MRNetworkLatencyModel Protocol

MRNetworkLatencyModel.h

```
//
//                        .
//
//
//                                  11/1 /12.
//            ( ) 2012                 .                    .
//

#                   /          .


– (               )
```

MRNormalDistrLatencyModel Class

MRNormalDistrLatencyModel.h

```
//
//                          .
//
//
//                                11/1 /12.
//            ( ) 2012              .                  .
//

#                 /          .



          (         ,       ,          )
          (         ;       ;          )

+ (  )              (             )
(                )
– (  )              (             )
(                )
```

MRNormalDistrLatencyModel.m

```
//
//                          .
//
//
//                                11/1 /12.
//            ( ) 2012              .                  .
//

#       "                         . "



+ (  )              (             )
(                )

!

– (  )              (             )
(                )

!
!      (    )
!   !
!   !
!
!


– (  )

!                           1.0                  0.2
```

```
– (          *)

!                                        "                    (       % ,          % )",
     ,


– (               )

!          (               )                  (    .    ,    .                ,
0.001 )
```

MRSimulation Class

MRSimulation.h

```
//
//              .
//                        –
//
//                                3/10/13.
//            ( ) 2013              .                  .
//

#                 /          .
```

```
          (          ,      )          *
          (          ,        )
          (          ,        )
          (          ,        ,          )                *
```

```
#             –
+ (   )
+ (   )                    (          *)              (              )
– (   )              (          *)              (              )

#             –
– (     )
– (     )
– (     )
– (     )
– (     )

#             –
– (     )
– (     )

#             –
– (     )                        (     ( )(     ))            (              )
        (          )
– (     )                  (              )
```

MRSimulation.m

```
//
//              .
//                        –
//
//                                3/10/13.
//            ( ) 2013              .                  .
//

#       "            . "
```

()
!

(, ,) *

–
– ( )

–

+ ( )

!

+ ( ) (*) ( )

!

– ( )

! ( )

– ( ) (*) ( )

!
! ( )
! !
! !
! !
! !
!
!

–

– ( )

! (

```
!                              .
!
!
!                            .0
!
!         ("  %                 %   %                 ",
!   !                    ,
!   !                 .                ,
!   !                      )
!
!                           2.0


- (    )

!


- (    )

!


- (    )

!         ("          ")


- (    )

!       .


#            -

- (    )

!         ("                     ")
!      (    .                                        )
!   !               ("       ")
!
!   !               ("%   ",                              "%          ",
(          )    .                        )
!


- (    )

!      (    .                !                          )
!   !                           (         )(    .       /    .              )-2
!   !
```

```
– (     )                          (     ( )(     ))             (                )
        (          )

!             (      ,
!   !               ()
!   !             (          0)
(       –1)
!     )


– (     )                    (                )

            *
!


           (                                        0.0 )

              (!           )
!
```

MRNetworkSimulation Class

MRNetworkSimulation.h

```
//
//                     .
//                         –
//
//                                3/10/13.
//            ( ) 2013               .                   .
//

#       "             . "
#       "                  . "
#       "                     . "
#       "                       . "
#       "                          . "



          (         ,       )
```

MRNetworkSimulation.m

```
//
//                     .
//                         –
//
//                                3/10/13.
//            ( ) 2013               .                   .
//

#       "                    . "


                                ()
```

```
#            –

– (  )              (         *)              (              )

!
!      (    )
!   !                              4.0
!   !                                0.
!   !

!
!
```

```
#            –
```

```
– (     )

!
!
!                                        .                          100
!                                        :                  .

– (     )

!
!          ("                  %      ",
                 .                                    )

– (     )

!
!
```

MRUni▫edAnomalySimulation Class

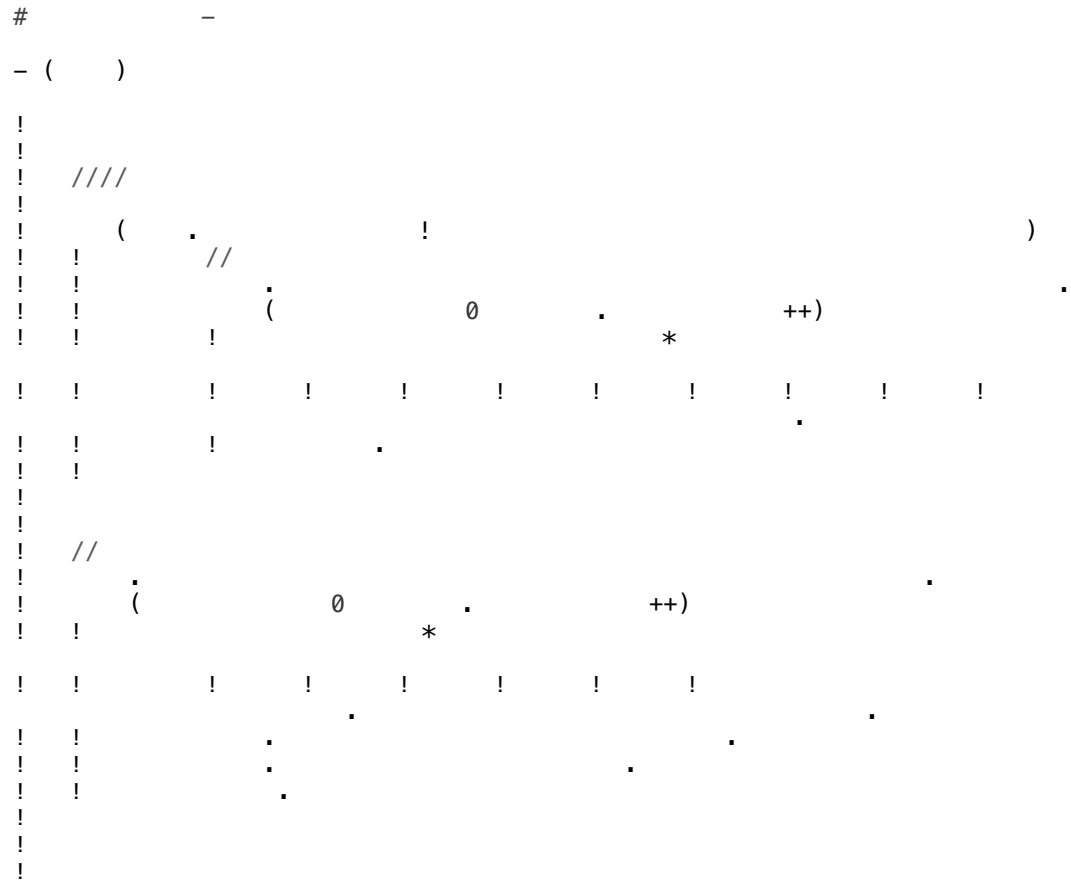
MRUni▫edAnomalySimulation.h

```
//
//                          .
//                       _
//
//                              4/4/13.
//           ( ) 2013               .                  .
//

#       "                   . "
#       "                   . "
#       "              . "
#       "                   . "

               (          ,                      )
!                                 ,
!                                        ,
!
```

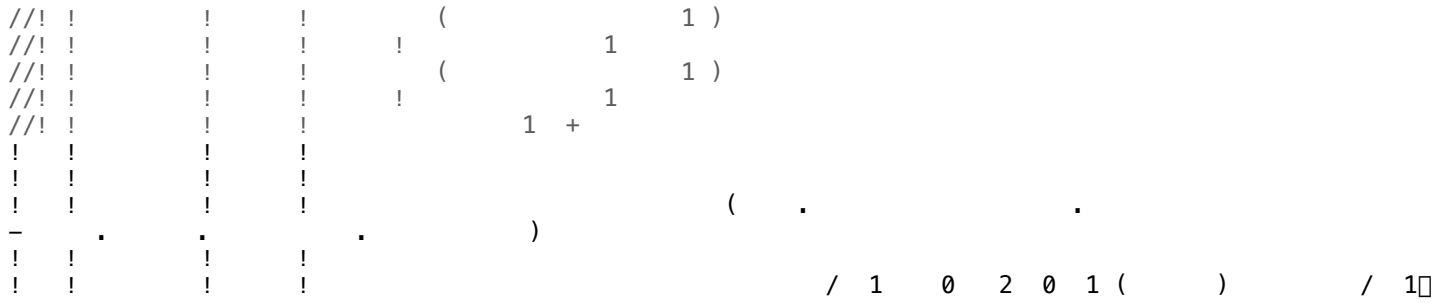
```
          (          ,       )
          (          ,       )
          (          ,       )
          (          ,       )
          (          ,       )
          (          ,       )
          (          ,       )

          (          ,       )
          (          ,       )

          (          ,     )        *
          (          ,     )        *
```

MRUni▫edAnomalySimulation.m

```
//
//                          .
//                       _
//
//                              4/4/13.
//           ( ) 2013               .                  .
//

#       "                         . "


                                    ()
!

          (          ,     )              *
          (          ,       )              *
          (          ,       )              *
```



```
!   //
!       .                          "  "
!       (            0       .
```



Main

main.m

```
//
//      .
//                        –
//
//                                3/10/13.
//            ( ) 2013                .                    .
//

#                  /          .
#       "                 . "
#       "                   . "
#       "                        . "
#       "                          . "

#            –

//#               ! !      !      !      !      !      !      !      !      "
         "

//#                                  !   !      !      !      !      "    –
                   "
//#                                  !    !      !      !      !      "
                   "
//#                                 ‼      !      !      !      !      "
                   "

//#                                        !   !      !      "          (
                )"
//#                                  !  !      !      !      !      "          (
               )"
//#                                  !  !      !      !      !      "          (
               )"


#            –


#            –

#                              !!      !
```

* (

```
!   !         !                                                  + 1
!   !         !          (             0                 ++)
!   !         !      !                 *                                "%  –
%   (% )",                                      , (          * + ),
!   !         !      !                                *
                                                            (                /
3.0)
!   !         !      !
!   !         !      !         .
!   !         !      !         .                    (                    /3.0)
!   !         !      !         .                     .                  *
!   !         !      !
!   !         !      !         .                              /2
!   !         !      !         .
!   !         !      !
!   !         !      !         .
!   !         !      !         .
!   !         !      !         .
!   !         !      !
!   !         !      !         .
!   !         !      !
!   !         !      !
!   !         !
!   !
#
!   !
!   !
!   !
#
!   !             (             0                .        ++)
!   !         !
!   !         !              *
!   !         !
!   !         !              *                                  "%  –      %
(% )",                                 ,  ,
!   !         !                          *
                                  (               /3.0)
!   !         !
!   !         !         .
!   !         !         .                    (                    /3.0)
!   !         !         .                     .                  *
!   !         !
!   !         !         .                              /2
!   !         !         .
!   !         !
!   !         !         .                                    + 1
!   !         !         .

!   !         !         .
!   !         !
!   !         !         .
!   !         !         .                        20.0
!   !         !         .                               .         / 2.0
!   !         !
!   !         !
!   !
#
!   !
!   !
!   !
#
!   !             (             0                .        ++)
!   !         !
!   !         !              *
```

!

Appendix C: Hardware Implementation

Main

Main.ino

```
/*

         20     2013


 */

#            .
#             .
#        "      . "
#        "               . "


////////////////////////////////////////////////////////////////////////////////
//////////////////////
#            –


!
!


                                 (                          )


////////////////////////////////////////////////////////////////////////////////
//////////////////////

#            –
              ()
             ()

#            –
                          ()
                         (                    ,                              )
                    (                          )
                  (                         )

#            –
             (       )

#            –
                ()
               ()
                (                        )
                   (                       )
                (                        )

#            –
                ()
               ()
                  ()
                   (     *          )

#            –
                   (                 )
                (                 ,              )
```

```
////////////////////////////////////////////////////////////////////////////////
//////////////////////
#           -

     *      4
#             1 !   !      0
#             2 !   !      1
#             3 !   !      2
#             4 !   !      3

#                  !           1
#                ! !           2

#                !  !      (                       )
#                !  !      (          !            )



                (23)
                                //


                   ""

#           -



////////////////////////////////////////////////////////////////////////////////
//////////////////////
#           -

                          ()

!                   .          ()


                         (                ,                          )

!                      ""
!              +         .
!              +  ','
!              +         .
!              (      ,          )


                    (                           )

!             .         (       .         ,                          )


                  (                      )

!
!          .       0
!          .                      .          ()

!                       (           ,        )
```

```
////////////////////////////////////////////////////////////////////////////////
//////////////////////////
#            –

             (       )

!               (   ,     )
!        ( 00)
!               (   ,    )
```

MRLeanTimeRecord Class

MRLeanTimeRecord.h

```
#
#

#          "          . "



!                                    ,
!                                  ,
!


!
```

–

(,
)

!

```
!


                        (              )

!       –                   (    )

!   //
!      (    .      ()                )
!   !               .       ("                      ")
!   !              (    )   //
!

!   //
!          (        !              )
!   !               .     ("                              ")
!   !               .       (     )

!   !           (                 )
!   !         !                   .     (     )
!   !
!   !         !                   .     (     ,          )
!   !

!   !             (1000)
!

!       –           ()


                             ()

!   //                                  '
!          .     ("      ")
!          .       (    .    ())

!   //                        '
!                      .       ()
!          .     ("           ")
!          .       (  )

!   //                        '
!
!       .             (   )
!          .     ("     ")
!          .     (      ,   )
!          .     (" ")
!          .     (    4 ,   )
```