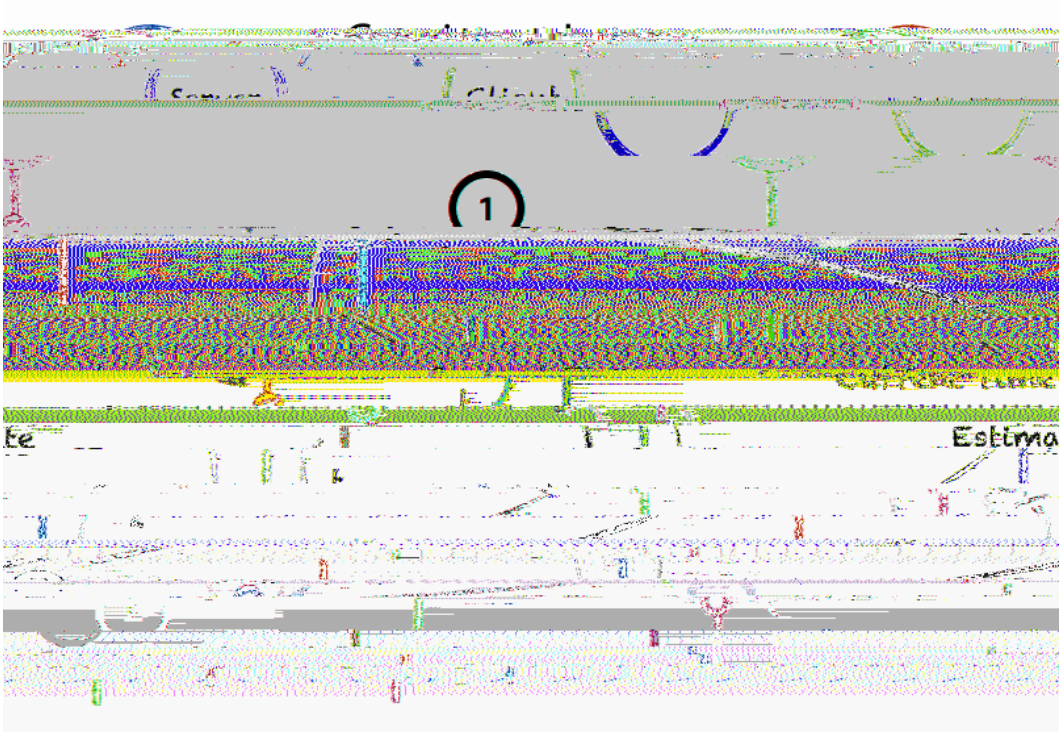
TABLE OF CONTENTS

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:

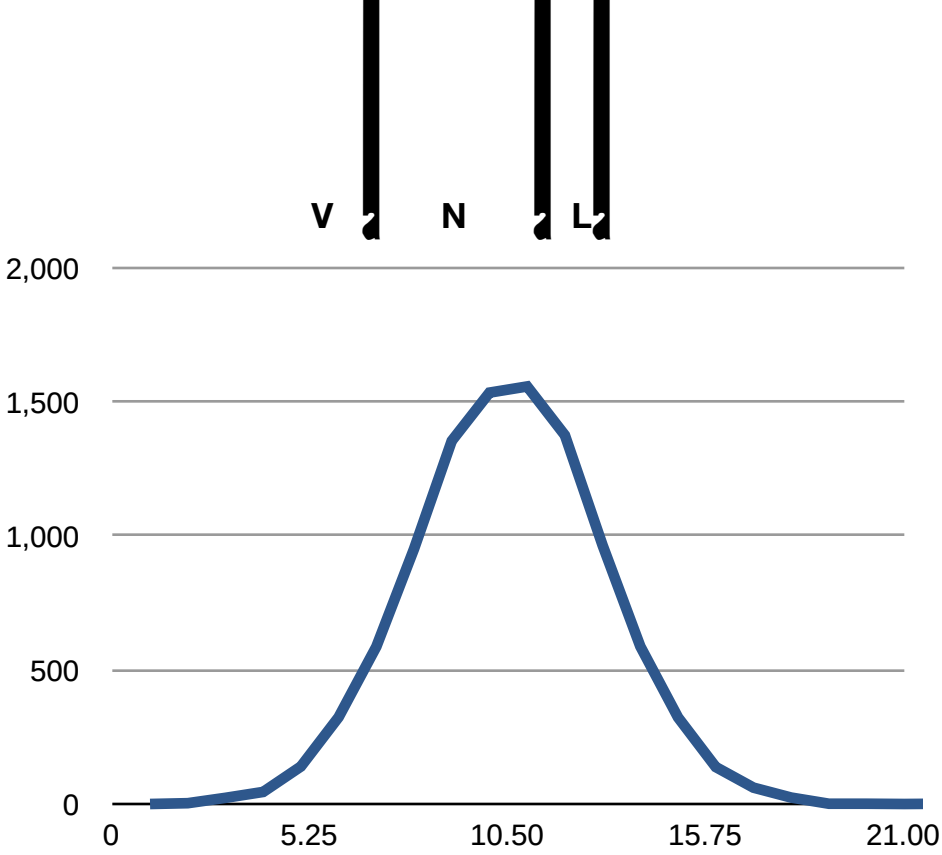
Adaptable to changes in overall network latency behavior:

Works well in both low and high latency volatility:

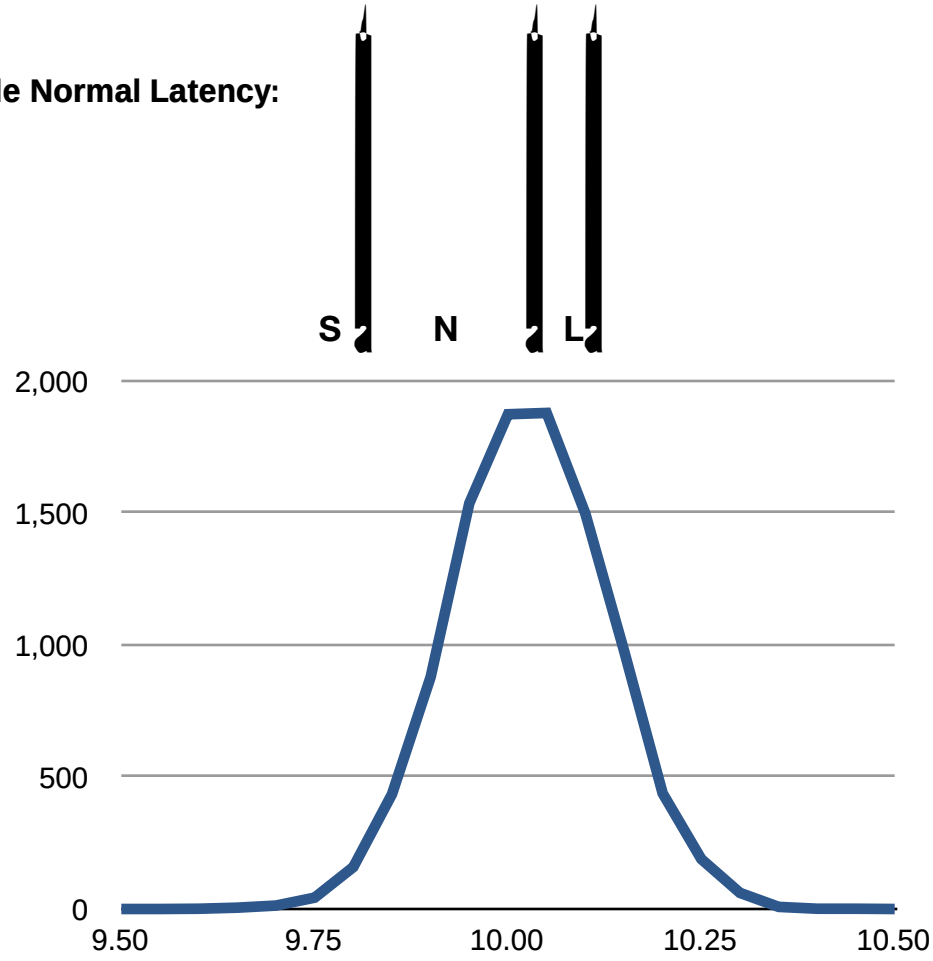
Simulation Results

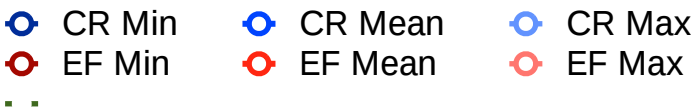
IMPLEMENTATION

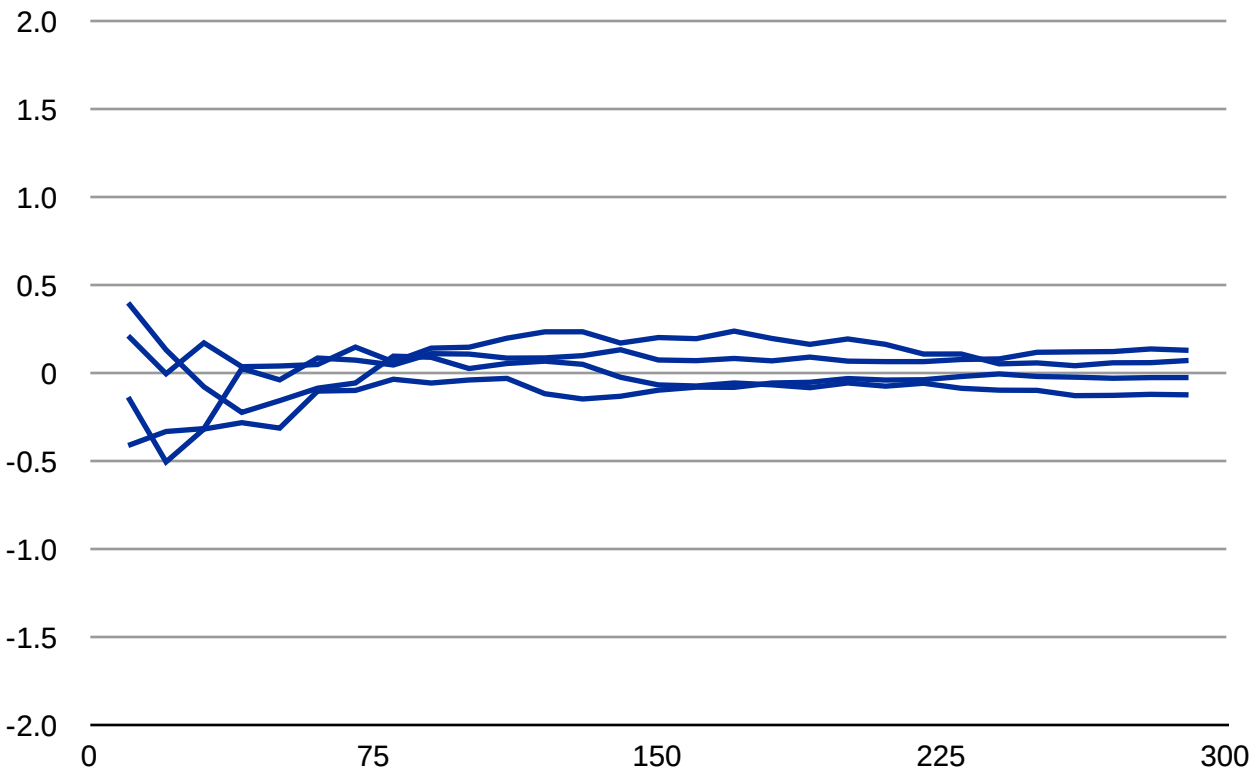
“Long-Tail” Normal Latency:

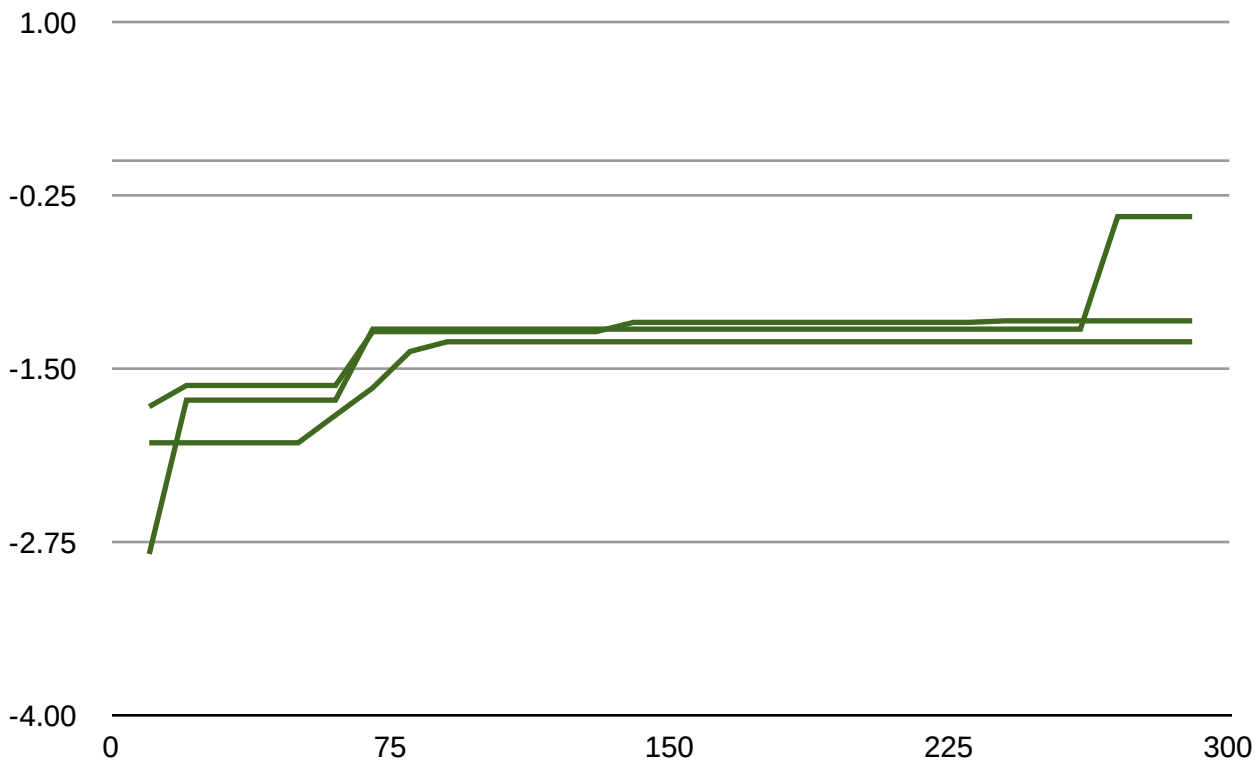


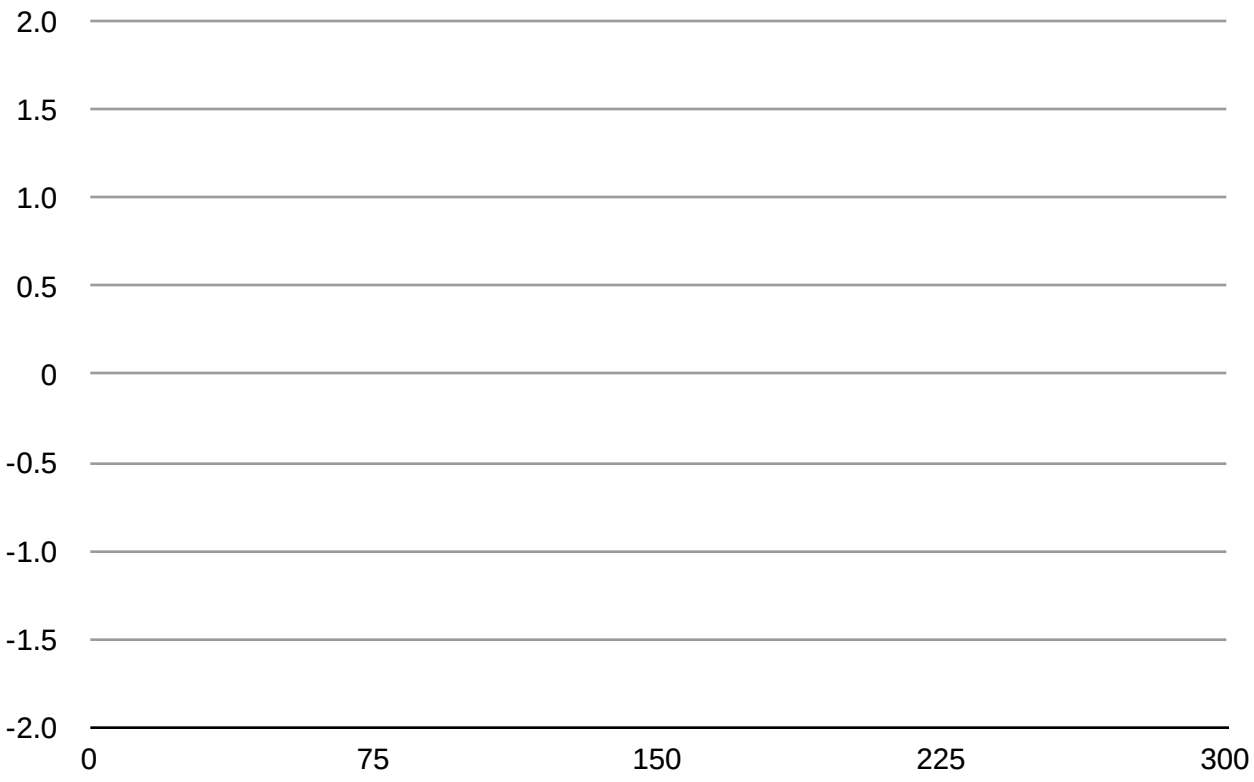
Stable Normal Latency:

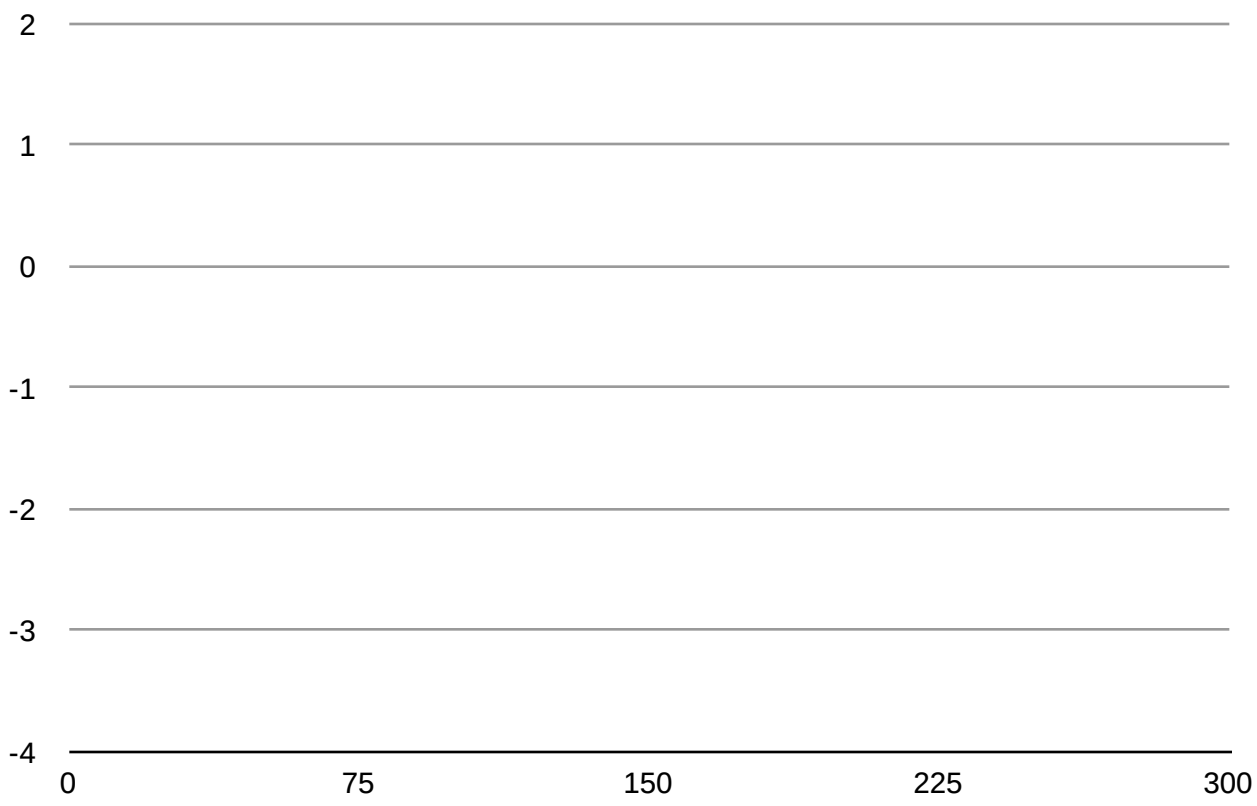



CR Min
CR Mean
CR Max
EF Min
EF Mean
EF Max


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

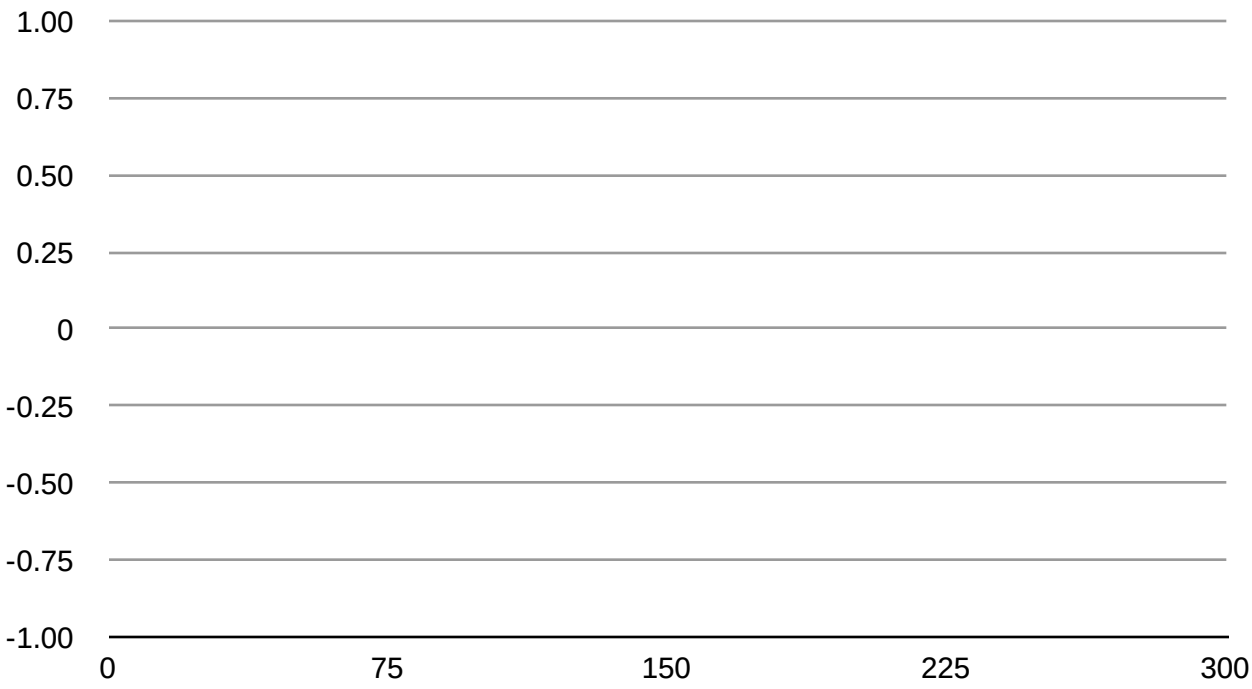
ALGORITHM IMPROVEMENTS

References

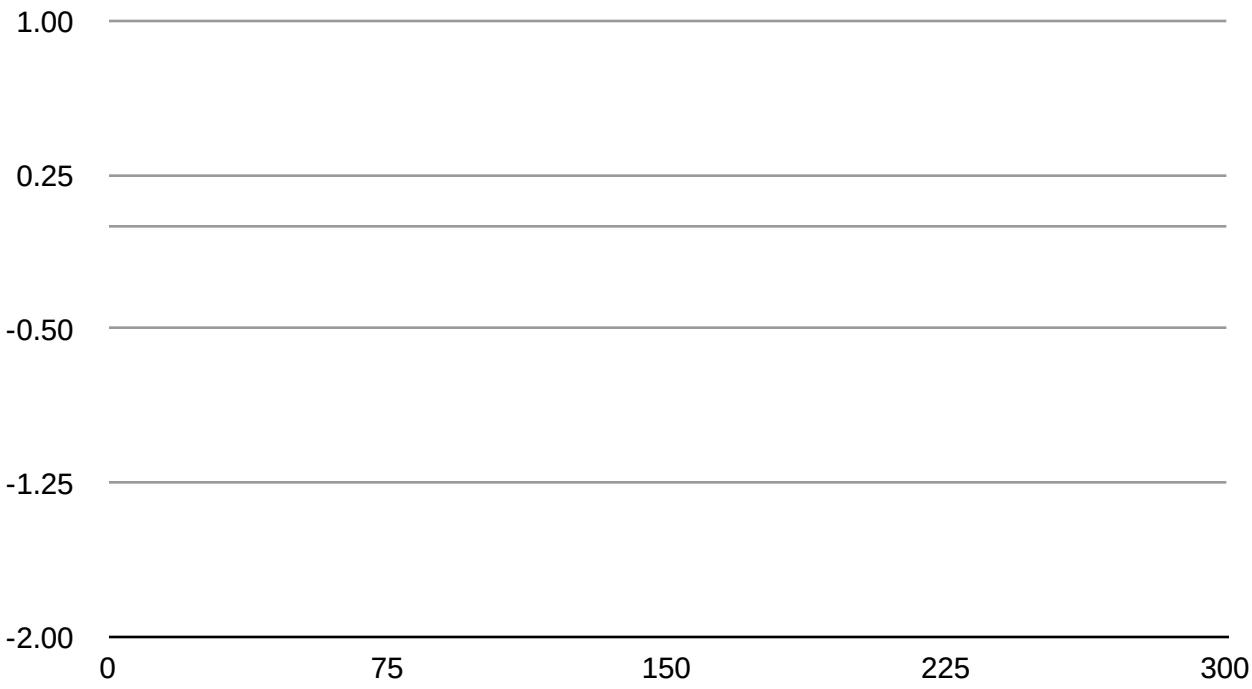
Appendix A: Simulation Results

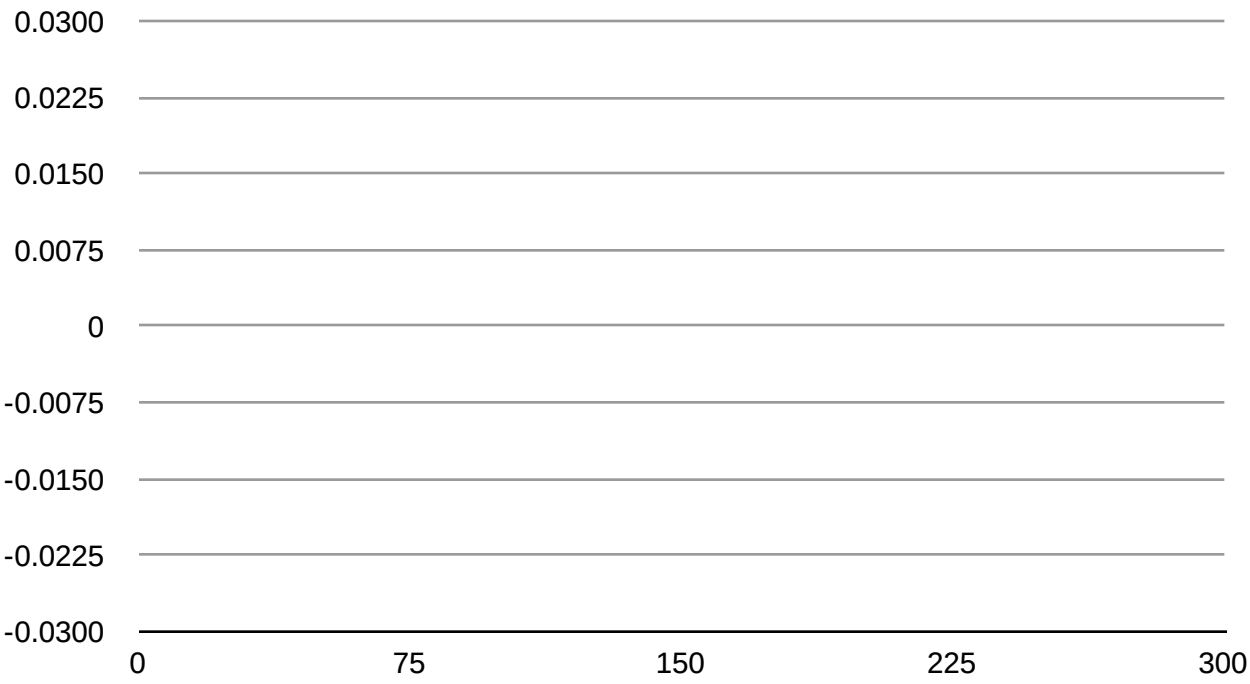
EXPERIMENT #1: BASE TIME RECORD SET

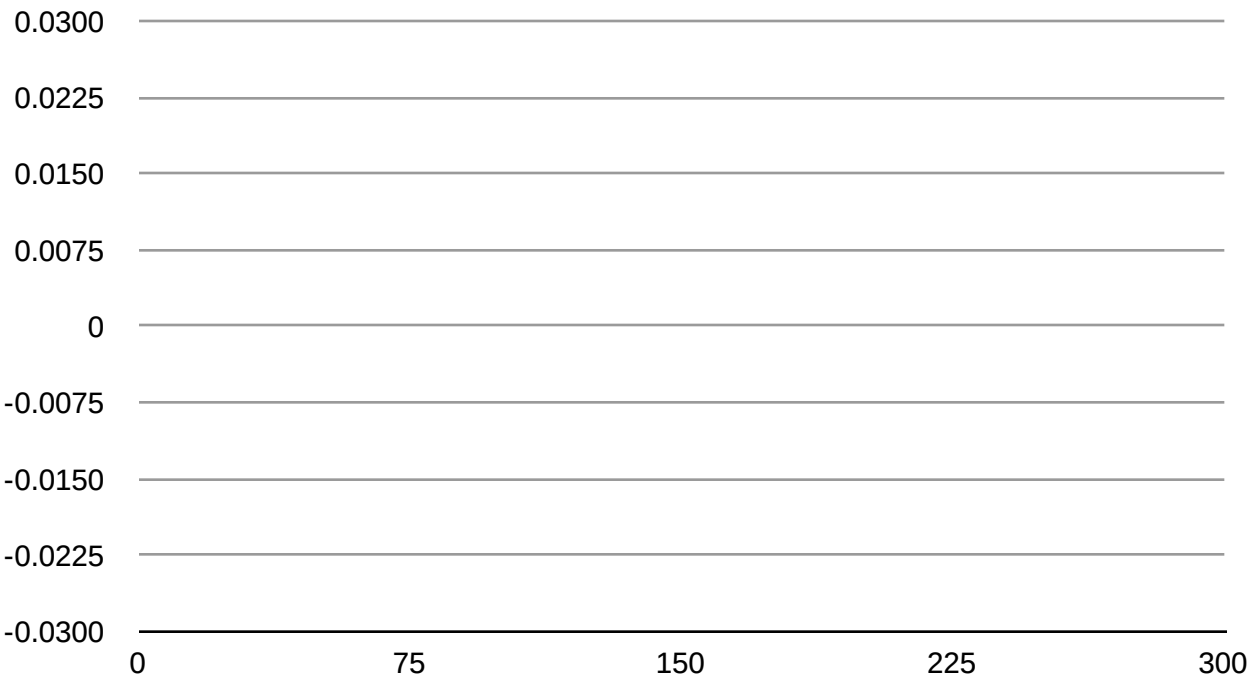
( ) + (+1)∗( )


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

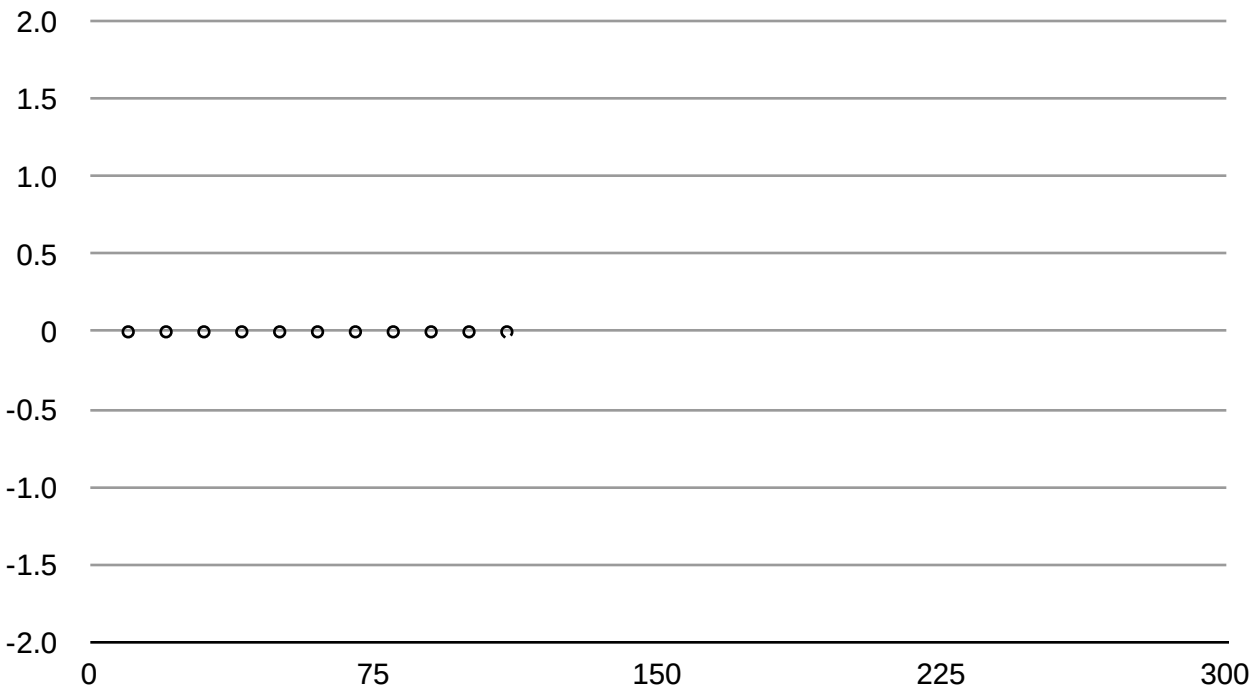

1.00
0.25
-0.50
-1.25
-2.00
0
75
150
225
300

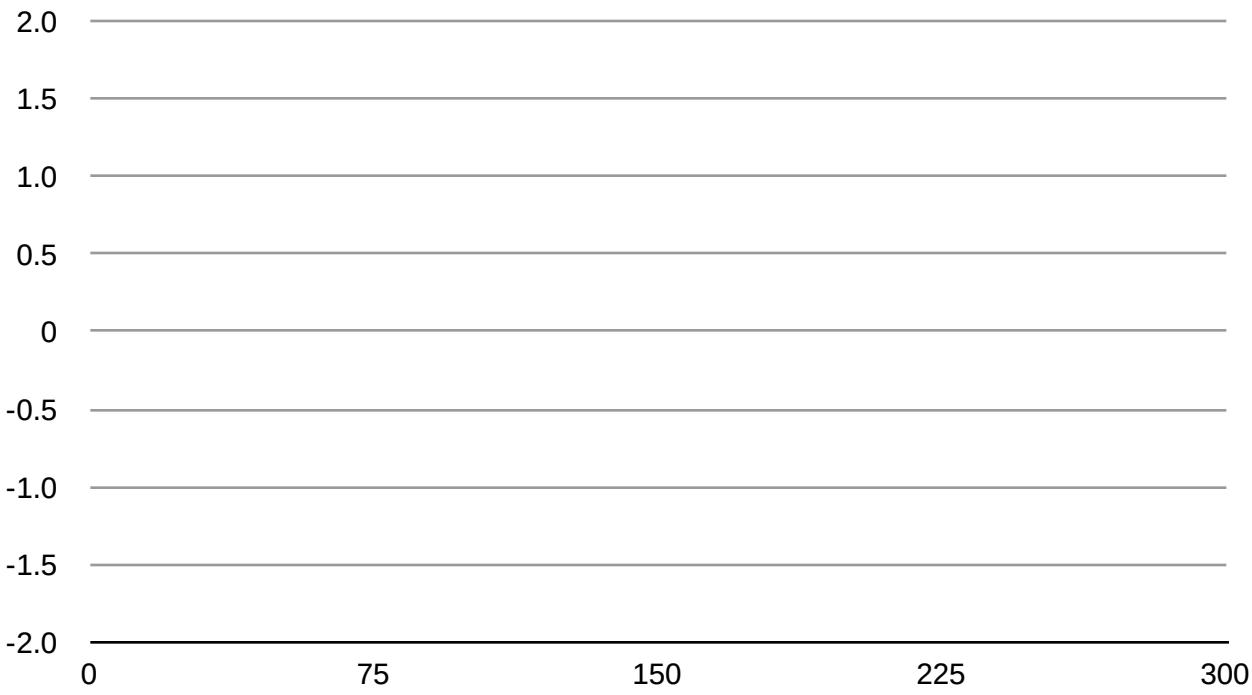

0.0300
0.0225
0.0150
0.0075
0
-0.0075
-0.0150
-0.0225
-0.0300
0
75
150
225
300

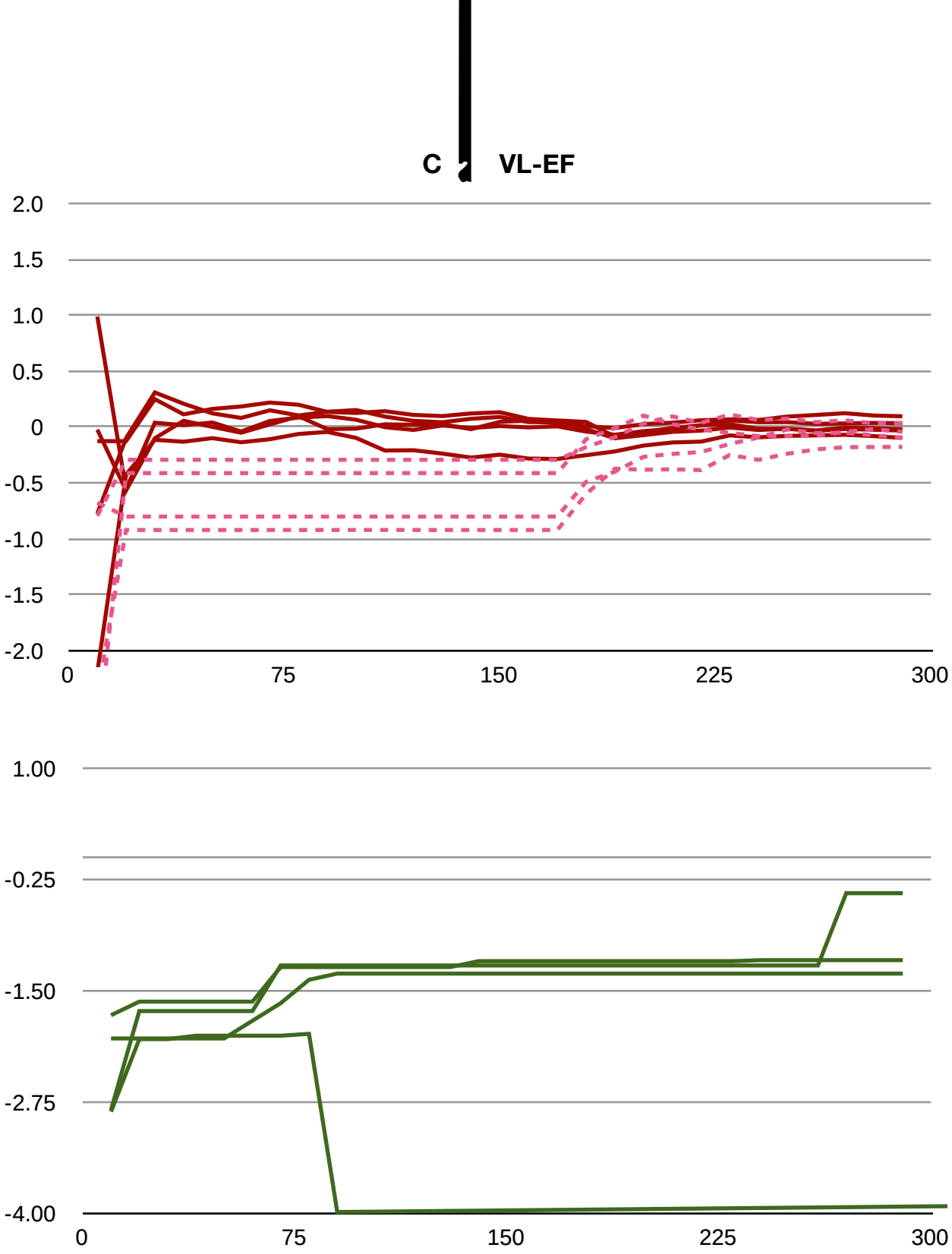

0.0300
0.0225
0.0150
0.0075
0
-0.0075
-0.0150
-0.0225
-0.0300
0
75
150
225
300

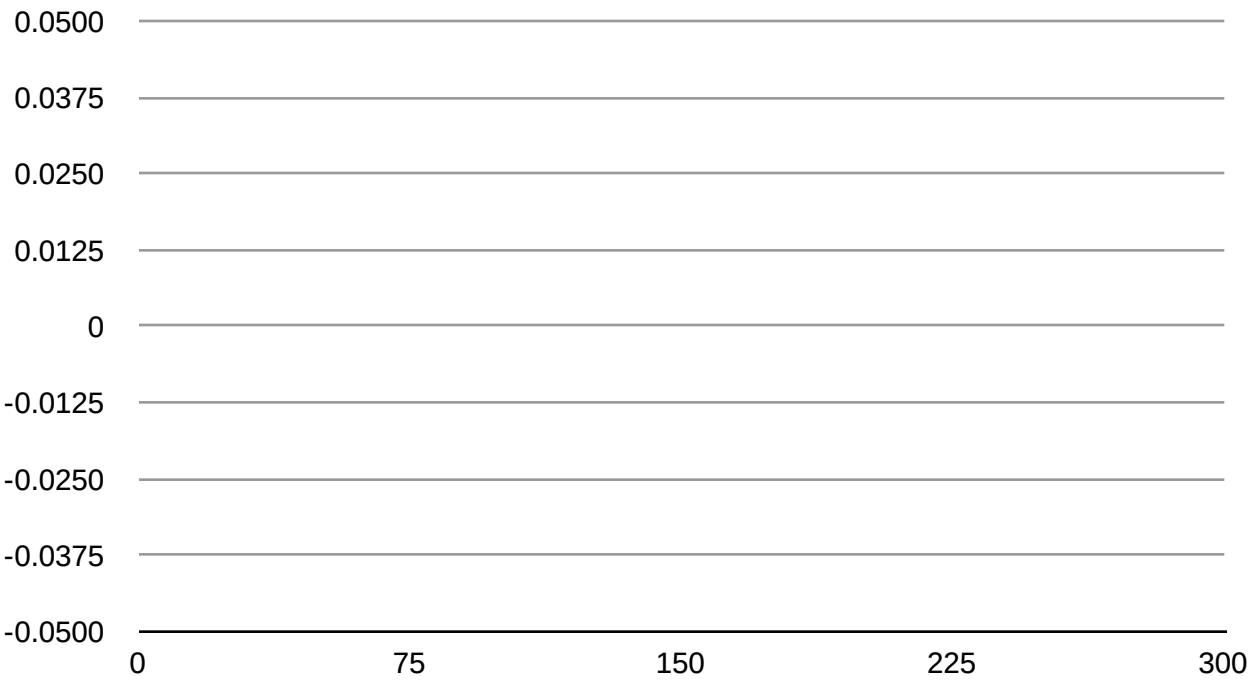
EXPERIMENT #2: CLIENT DISCONNECT

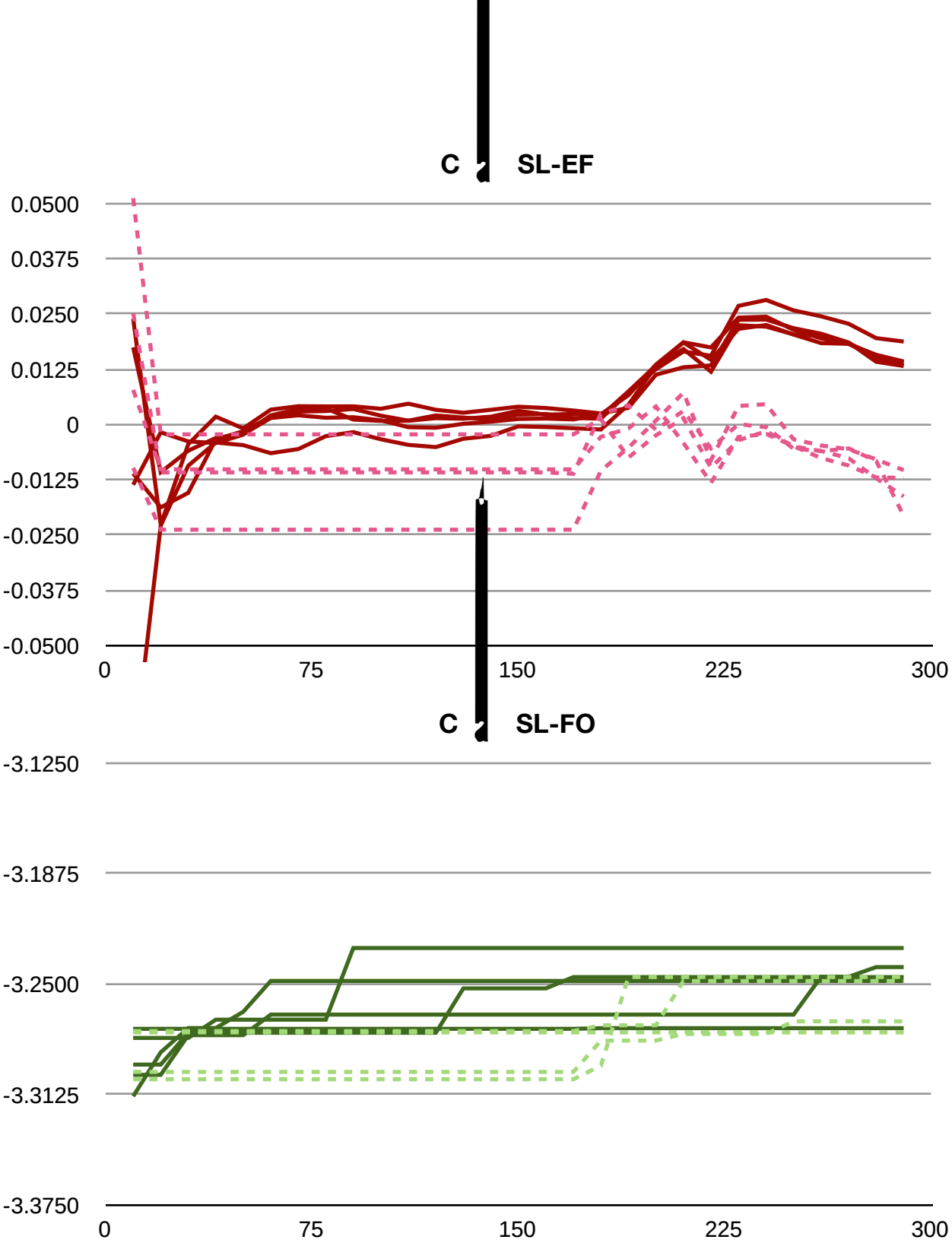
Tests:


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

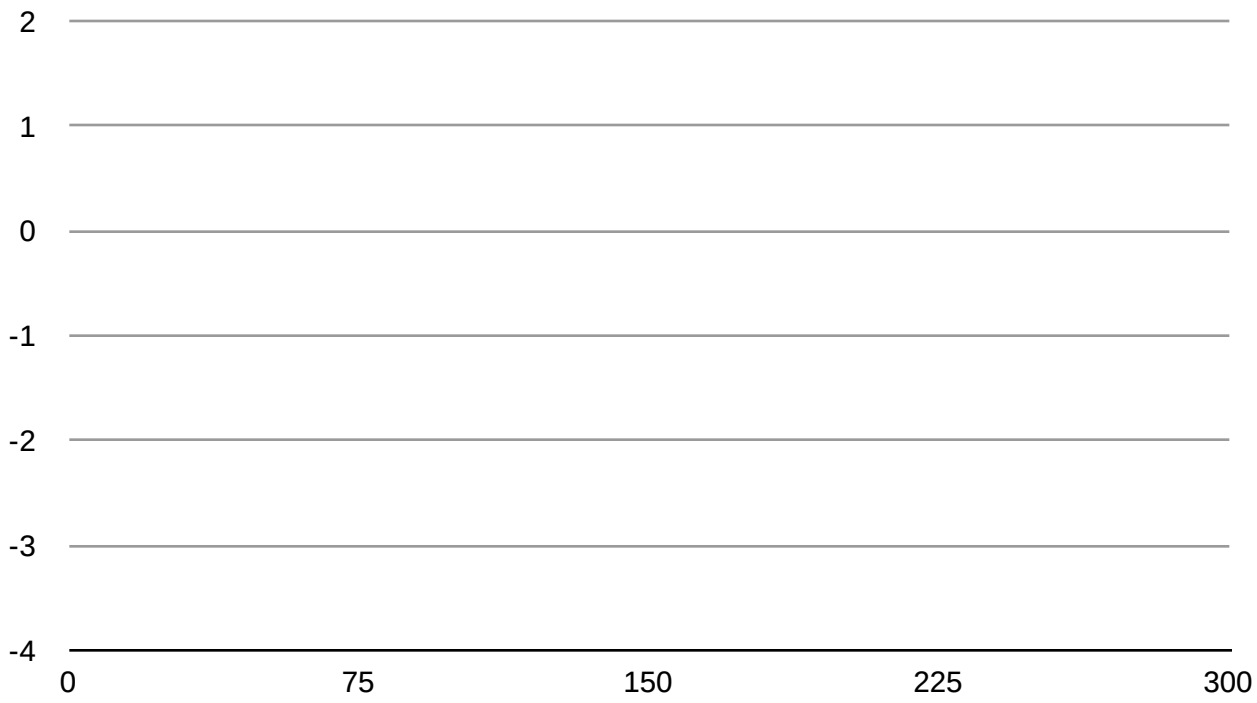

2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
0
75
150
225
300

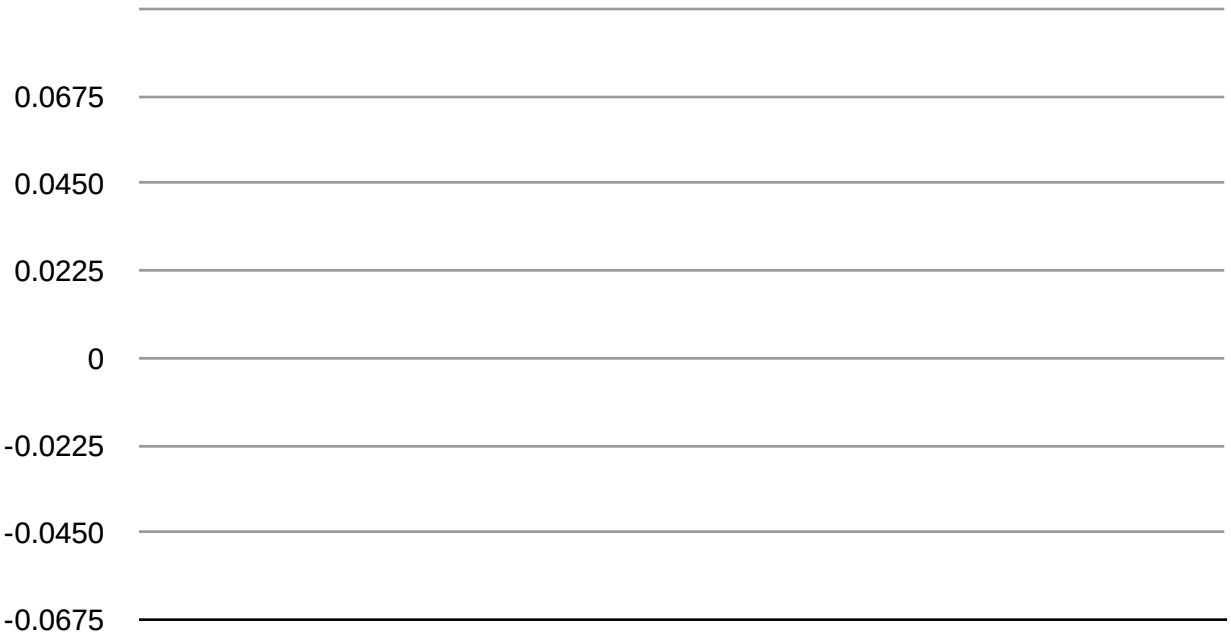

C
VL-EF
2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
0
75
150
225
300
1.00
-0.25
-1.50
-2.75
-4.00
0
75
150
225
300


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 1    ()              )   ,      1 0 0
                                          ‘
                     ‘


                                          ‘


                                                ‘                          ‘
```

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

#           -
        (     ,      ,                 ,         )
```

return

```
– (        *)

!      ((        *)   .
          .        ).    ,

– (        *)

!      ((        *)   .        ).    ,

– (        )

!      ‘  .     .    +   .     *
(   .           + 1),

– (        )

!          .     .          ,

#        –

– (   )

!            ,

– (   )        (   )

!               (   )
!   !          (      !      )
!   !     !                     ,
!   !     !
!   !     !       (       )
!   !     !    !        .                    ,
!   !     !    !         .
(   .               ‘        ) , // +   .        ) ,
!   !     !
!   !     !    !        .          ,
!   !     !
!   !
!

– (   )               (          )    ‘
(          )

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


‘
‘ ‘

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


– (    )

!        .             ,


#            –

– (    )                       (              )

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


#            –              ‘

– (    )            (              *)

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


– (    )           ,       (                    *)

!                            (


                                        ‘
                                      ‘


                        ‘
```

–

()

(, ,) * ,
(;

– ( ) (*)

‘

```
!    !
!
!
!       (          0.0)
!    !                0.0;
!
!                                       (     /          ),
!                                           ,
```

```
#             –                 (          )

                                   (          )

– (     )

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

```
                                   ‘                    ‘
```

MRTimeRecord Class

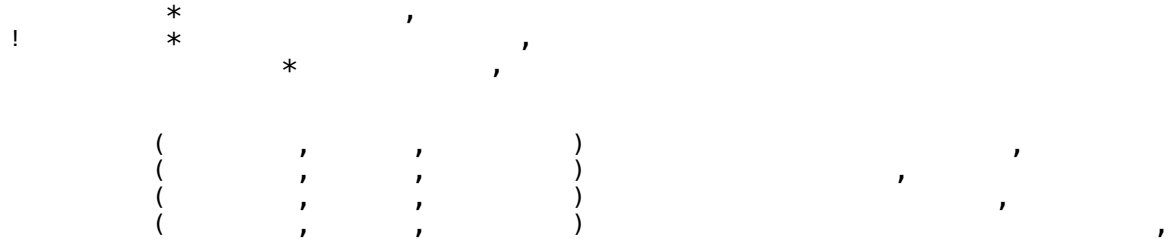
MRTimeRecord.h

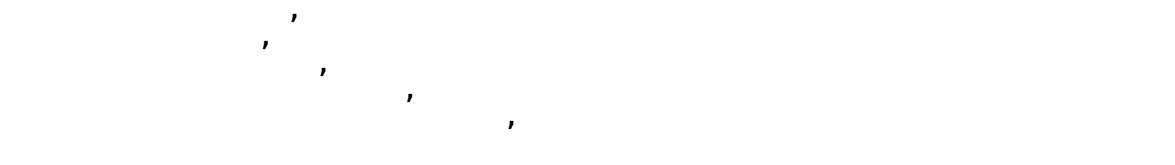
```
//
//                .
//
//
//                                2/21/13.
//            ( ) 2013               .                   .
//

#                /         .

                 ,

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

#           –

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

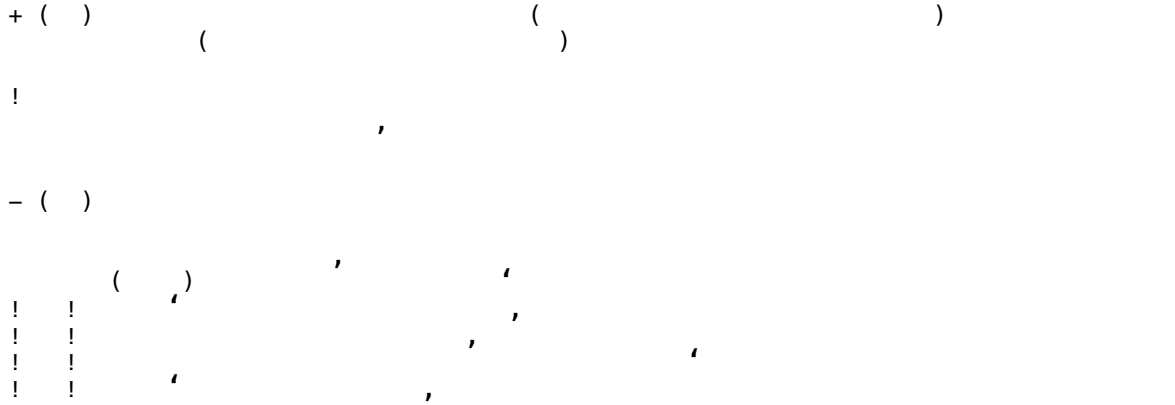
```
#            –
+ (  )                               (    )
(              )                  ,
+ (  )                               (    )
(              )                  ,
+ (  )                                (    )            ,

#            –
- (          *)                      ,
- (          *)                         ,
                                     ‘                                   ‘

                                     ‘                                   ‘
#            –
                                      ‘
               (          ,                                  )
!                                              ,
!                                           ,
!                                           ;
!
 ,


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

#            –
+ (  )         ,                     ‘
+ (  )                           (                            )
               (                 )                  (         )   ,
- (  )                 (                            )
               (                 )                  (         )   ,
- (  )                 (                            )
(    )                                  (               )
(          )   ,

#            –
- (          *)                     ‘       ,
- (          *)‘                               ,         ‘
                            ‘
               ‘                                         ‘
                            ‘                                                          ‘
                                      ‘                                   ‘
```

MRTimeRecord.m

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

#       "            . "


                              ()
```







! (* ,
)
! ! (! .)

‘

```
!          (                  !     ),

– (        *)

                                  ,

– (              )

!      (                )
!   !               –                                        ,
!          0.0;

– (              )

!      (                        )
!   !               –                                              ,
!          0.0,
```

```
#           -

#                                  (      )
(    .                                                    .

(    .                                                       .

(    .                                                       .

(    .                                                  .
0))))

                                  ()

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



#           -

+ (
```

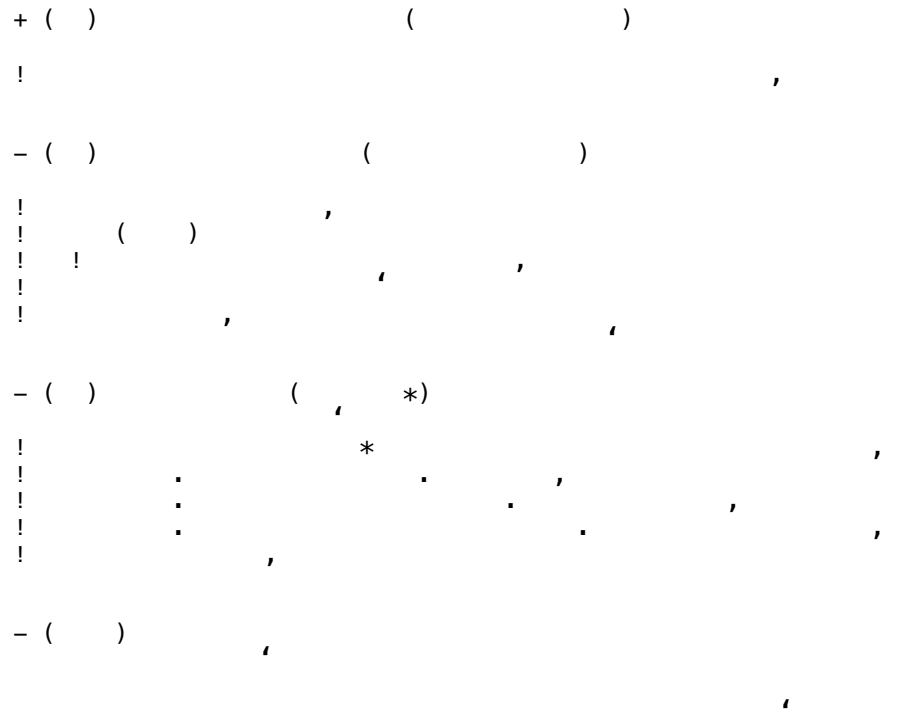
MRTimeUpdateMessage Class

MRTimeUpdateMessage.h

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

#       "                . "



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

+ (  )                      (              )         ,
– (  )                  (              )         ,

– (    )                      ‘      (              )              ,
```

MRTimeUpdateMessage.m

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

#       "                    . "
#       "                   . "


                                ()

          (          ,       ,           )                        ,
          (          ,       ,           )                           ,




– (  )

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



MRNetworkMessage Class

MRNetworkMessage.h

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

#                  /          .
```

,

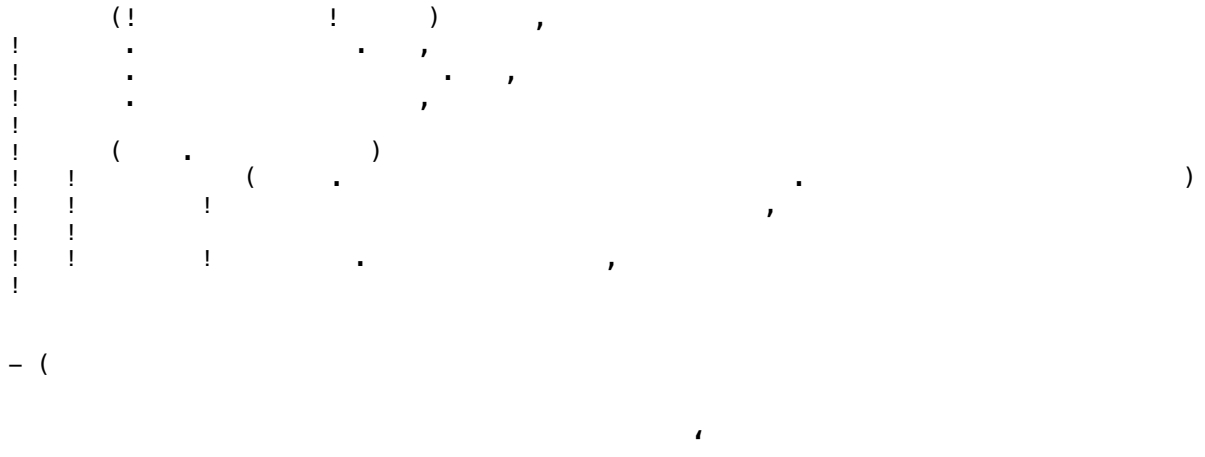
‘

+ ( )

! ,

– ( )

! ,
! ( )
! !



MRCristianTimeServerNode Class

MRCristianTimeServerNode.h

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

#       "             . "
#       "                  . "


          (         ,       ,         )
```

‘

MRCristianTimeClientNode Class

MRCristianTimeClientNode.h

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

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


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

+ (  )                          (              )              ,
– (  )                          (              )              ,

+ (  )             (          *)                      (              )             ,
– (  )             (          *)                      (              )             ,

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

#            –
– (    )                     ‘ (              )       ,
                             ,

                 ‘                                ‘
                 ‘                                ‘

                                    ‘
```

MRCristianTimeClient‘Node.m

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

#       "                         . "
#       "                     . "


                                   ()

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

```
//!
//!        0.0,
!              .        .          ,


– (               )

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

```
#                 –

– (       )                          (                  )

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

                                    ‘
```

MRNetworkNode Class

MRNetworkNode.h

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

MRNetworkDirectory Class

MRNetworkDirectory.h

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

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


+ (                    *)                ,

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

– (    )     ,                  ‘

– (  )               (                *)    ,

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


                ‘

MRNetworkDirectory.m                                                    ‘

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

#       "                   . "
#       "                      . "


                                ()
!                  *              ,
!                             ,


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

– (    )               (               )       ,
```

– ( ) (*) ,

* ,

+ (*),

! (!)
! ! ,
! , ,

– ( )

,
( )
,
,

– ( )

! ,
! ,
! 10
! 1.0 ,
!

,

```
!   !          ),
!

– (    )                  (                *)

!   //

– (    )               (              )

!         .                                    (       )         0,
!          (    .                   .           .                      )
!   !              .     ‘                              ,
!
!
!          ‘                        0.0,
!       (          *                .                  )
!   !                 ‘

                                          ‘                ‘
```

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                .                    .
//

#       "               . "

                                                             ,
                                                           −1,
```

()
! ,

(, ,) * ,

–
– ( ) ,

–

+ ( )

! ,

+ ( ) (*) ( )

! ,

– ( )

! ( )
 ‘ , ‘
– ( ) (*) ‘ (‘)

! ,
! ( )
! ! ,
! ! ‘ ,
! ! ‘ , ,
! ! ‘ ,
!
! , ‘ ‘

–

– ( )

! (

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

– (    )                     ‘
!                    ,          ‘

– (    )
!                   ,        ‘

– (    )
!          ("           "),

– (    )
!       .                                  ,


#             –

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

– (    )

!      (     .                 !                          )
!   !                             (          )(     .        /     .               )–2,
!   !                                                    ‘
```

MRNetworkSimulation Class

MRNetworkSimulation.h

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

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



          (         ,       )                                  ,
```

MRNetworkSimulation.m ‘

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

#       "                   . "


                              ()
```

```
#            –

– (  )              (         *)              (              )

!                                                          ,
!      (    )
!   !                              4.0 ,
!   !                                0. ,
!   !
                          ,
!
!             ,   ‘                          ‘

                              ‘             ‘
#            –
```


‘

```
– (     )

!                ,
!                                    ,
!                                                    100
!                                  .                  .
!                                  .                  .          ,

– (     )

!                ,
!          ("             %      ",
                 .                                    ),

– (     )

!                                                    ,
!                    ,
```

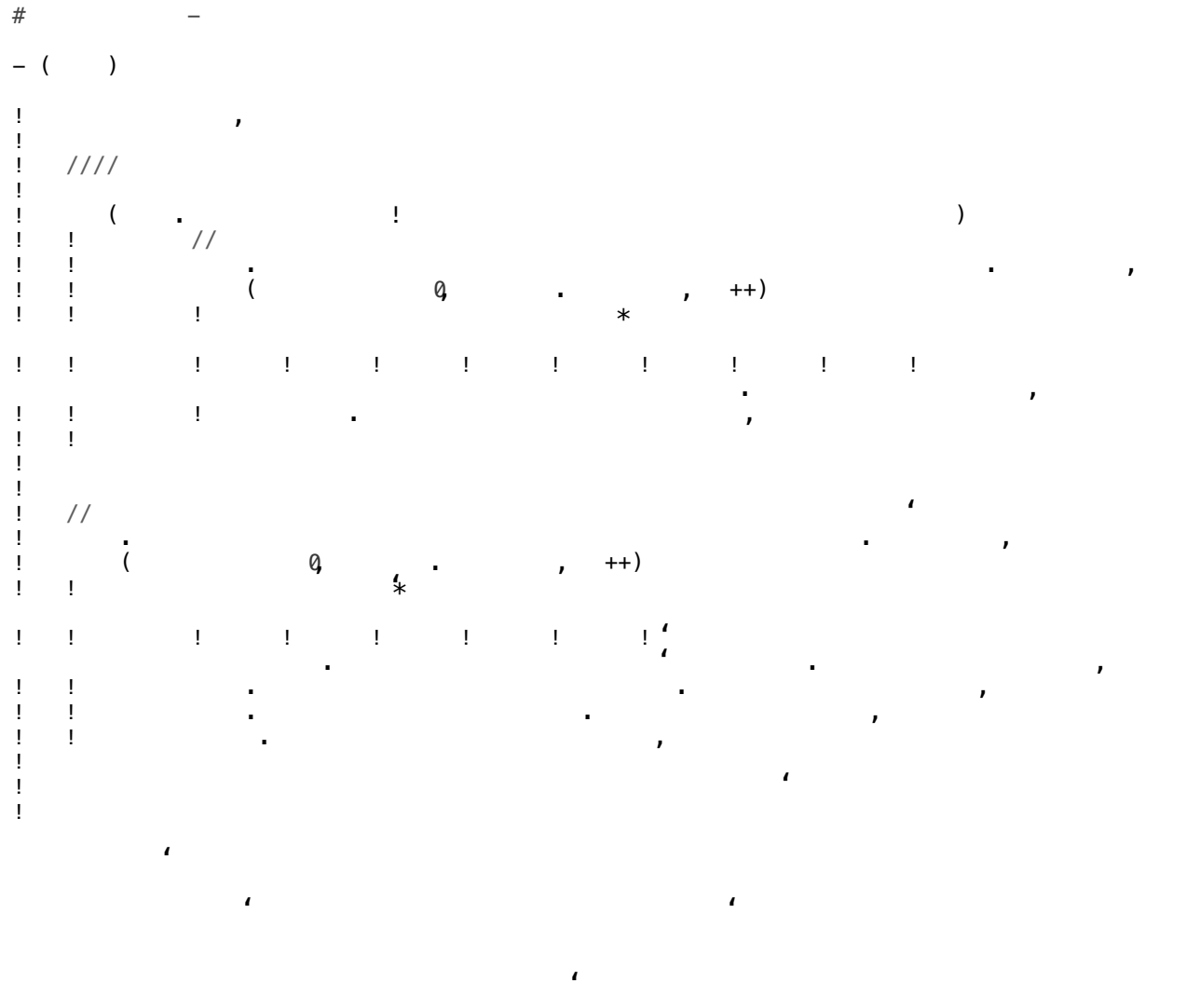
MRUni▫edAnomalySimulation Class

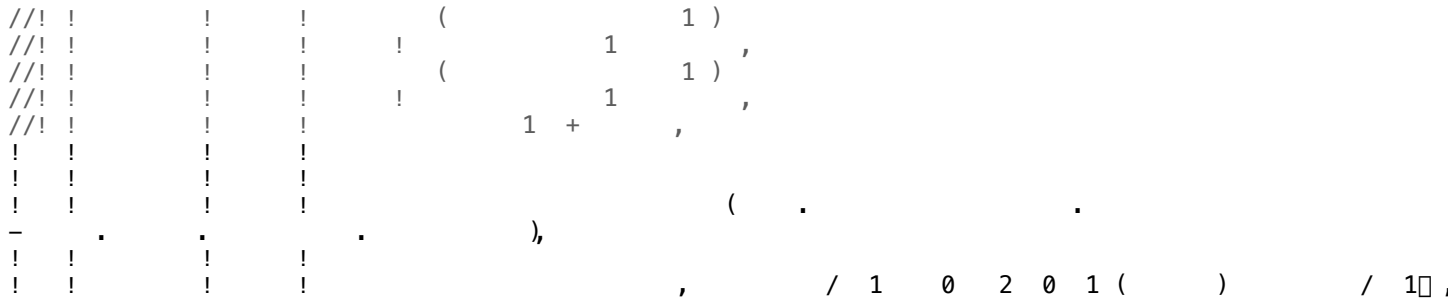
MRUni▫edAnomalySimulation.h

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

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

               (          ,                      )
!                               ,
!                                        ,
!
,



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

          (          ,       )        ‘                          ,
          (          ,       )                                   ,

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

MRUni▫edAnomalySimulation.m

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

#       "                         . "


                                    ()
!                         ,


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





Main

main.m

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

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

#            –

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

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

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


#            –


#            –

#                              !!      !
```

* (

!

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 ,    ),


                                                  ‘


                       ‘

                  ‘
```