Specification of Realtime Systems Using ASTRAL*

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Abstract

ASTRAL is a formal specification language for realtime systems. It is intended to support formal software development and, therefore, has been formally defined. The structuring mechanisms in ASTRAL allow one to build modularized specifications of complex systems with layering. A realtime system is modeled by a collection of state machine specifications and a single global specification.

This paper discusses the rationale of ASTRAL's design. ASTRAL's specification style is illustrated by discussing a telephony example. Composability of one or more ASTRAL system specifications is also discussed by the introduction of a composition section, which provides the needed information to combine two or more ASTRAL system specifications into a single new one. Finally, this paper discusses the current status of the ASTRAL software development environment.

Index Terms - Formal methods, Formal specification and verification, Assertions, Temporal logic, Realtime systems, Timing requirements, Software Tools, State machines, Composability, ASLAN, TRIO.

1. Introduction

A realtime computer system is a system that must perform its functions within specified time bounds. Realtime computer systems are increasingly being used in critical applications such as aircraft avionics, nuclear power plant control and patient monitoring. These systems are generally characterized by complex interactions with the environments in which they operate and strict time constraints whose violation may have catastrophic consequences. The need for these software systems to be highly reliable is evident.

The best way to improve software quality is to develop it formally. Existing informal software development methods and tools [Qui 85, HP 88, Gom 94] are often unable to

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* This paper is an extended version of two previous papers by the same authors [GK 91a, CK 93].

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provide acceptable levels of assurance for many realtime applications, because of the combination of complexity and critical requirements.

Although research in the area of realtime systems has been quite active, and a number of experimental environments supporting formal specifications have been developed (see Section 5), the search for adequate notations and tools is still open. The ASTRAL formal specification language for realtime systems and its associated support environment, which is currently being developed, are intended to provide a solution to the problem.

Because ASTRAL is intended to be used for specifying large and complex realtime systems it was designed to support specifications that are layered and compositional. Layering and composition are two complementary approaches to hierarchical system development. A layered specification method allows one to refine the specification of a process to show more detail, without changing the interface of the specified system. This is important because it allows designers to prove, test, or otherwise examine properties of a process whose behavior is specified abstractly, and then iteratively refine the behavioral specification to be as close to an implementation as appropriate for a given assurance level.

A compositional specification method allows one to reason about the behavior of a system in terms of the specifications of its components [Zwi 89]. That is, the behavior of a system comprising several component processes is completely determined by the component specifications. This is important because it modularizes a system's proof and allows for bottom-up development.

ASTRAL provides mechanisms for specifying critical system requirements, and a formal proof system for proving the satisfaction of the stated requirements has been defined. These proofs are divided into two categories: *intra-level* proofs and *inter-level* proofs. The former deal with proving that the specification of level i is consistent and satisfies the stated critical requirements, while the latter deal with proving that the specification of level i+1 is consistent with the specification of level i. Details of the formal proof system can be found in [CKM 94, CKM 95].

The ASTRAL specification language is intended to be executable. An executable specification language allows developers to treat specifications as prototypes. This is important because testing in the design stage, even before attempting proofs, can be a cost-effective means of finding design flaws [Kem 85, DK 94]. A translation scheme for translating ASTRAL to TRIO [GMM 90, MMP 96] was defined for an earlier version of the ASTRAL language [GK 91b]. More recently, the semantics of ASTRAL have been formally defined using both a model theoretic approach and an axiomatic semantic approach [CSK 94]. This provides a firm theoretical basis for the development of a software development environment with a specification execution tool as one of its components. The axiomatic semantics of the ASTRAL abstract machine can be found in [CKM 94].

The main intent of this paper is to give the reader an introduction to the language and to report on the status of the ASTRAL software development environment. In the next section the specification language is presented using a telephone system example to clarify the language components and their use. In section 3 the ASTRAL approach to composing system specifications is described and the telephony example is extended. Section 4 reports on the status of the ASTRAL software development environment, and section 5 discusses related work. Finally, conclusions drawn from this work and further areas of research are presented.

2. An Overview of ASTRAL

In ASTRAL a realtime system is described as a collection of state machine specifications each of them representing a process type of which there may be multiple statically generated instances plus a global specification, which contains declarations for types and constants that are shared among more than one process type, as well as assumptions about the global environment and critical requirements for the whole system.

Figure 1 presents the syntactic structure for an ASTRAL specification.

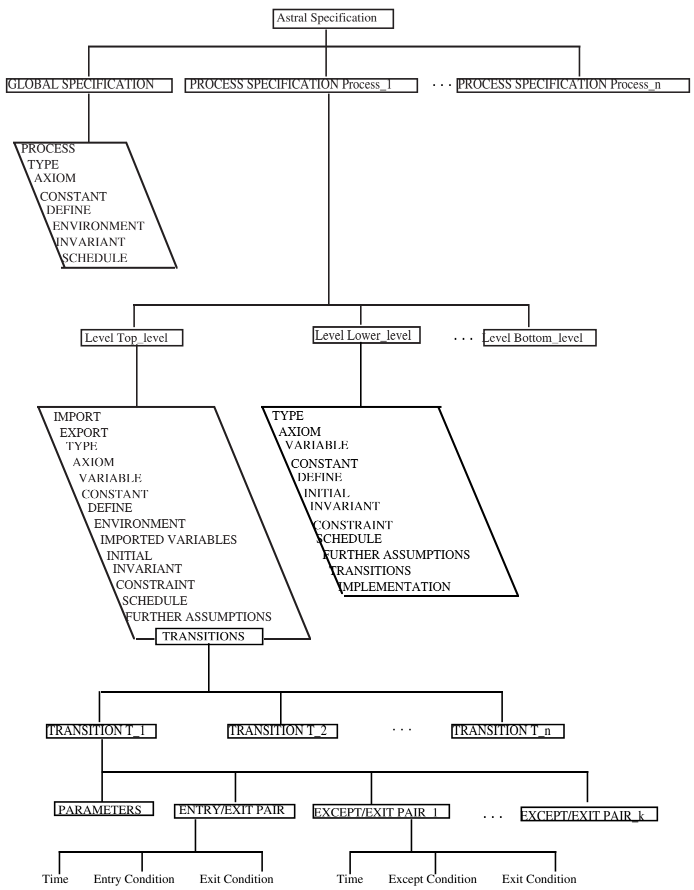


Figure 1: ASTRAL syntactic structure

An ASTRAL *process specification* consists of a sequence of *levels*. Each level is an abstract data type view of the system being specified. The first ("top level") view is a very abstract model of what constitutes the process (types, constants, variables), what the process does (state transitions), and the critical requirements the process must meet.

Lower levels are increasingly more detailed with the lowest level corresponding closely to high level code[1].

The process being specified is thought of as being in various *states*, with one state differentiated from another by the values of the *state variables* which can be changed only by means of *state transitions*. Transitions are described in term of pre- and post-conditions by using an extension of first order predicate calculus. Transition *pre-conditions* describe the constraints that state variables must satisfy in order for the transition to fire, while *post-conditions* describe the constraints that are fulfilled by state variables after the transition has fired. An explicit nonnull duration is associated with each transition. Transitions are executed as soon as they are enabled (i.e., when their pre-condition is satisfied).

Every process can export both state variables and transitions; as a consequence the former are readable by other processes while the latter are executable from the external environment. Inter-process communication is accomplished by broadcasting the value of exported variables and the start and end times of exported transitions.

In addition to specifying system state (through process variables and constants) and system evolution (through transitions), an ASTRAL specification also defines system critical requirements and assumptions on the behavior of the environment that interacts with the system. The behavior of the environment is expressed by means of *environment clauses*, which describe assumptions about the pattern of invocation of external transitions. Critical requirements are expressed by means of invariants and schedules. *Invariants* represent requirements that must hold in every state that may be reached from the initial state, no matter what the behavior of the external environment is, while *schedules* represent additional properties that must be satisfied provided that the external environment behaves as assumed.

In what follows the computational model of ASTRAL is first presented and then the main features of the language are discussed.

2.1 The Computational model

The computational model for ASTRAL is based on nondeterministic state machines and assumes maximal parallelism, noninterruptable and nonoverlapping transitions in a single process instance, and implicit one-to-many (multicast) message passing communication.

Maximal parallelism assumes that each logical task is associated with its own physical processor, and that other physical resources used by logical tasks (e.g., memory and bus bandwidth) are unlimited. In addition, a processor is never idle when some transition is able to execute. The maximal parallelism approach was chosen on the basis of separating independent concerns; that is, first demonstrate that a design is satisfactory, then, and only then, consider the scheduling problem imposed by a particular implementation's limited resources. This approach, advocated in [FP 88] for

[1] For space reasons layering of specifications is not addressed in this paper. The reader may refer to [CKM 95].

realtime systems and in [CM 88] for parallel systems, allows for much cleaner designs than an approach that starts with scheduling concerns. A design based on the structure of the system rather than on its scheduling problems will usually be easier to maintain and/or modify. In addition, architectures that meet the maximal parallelism assumptions are becoming more prevalent.

Process cooperation, which involves both communication and synchronization, may be achieved in essentially two ways: either by data sharing or by message passing [BST 89]. The interface specification of RT-ASLAN [AK 86b], which is an earlier realtime specification language developed by the Reliable Software Group at UCSB, is an example of modeling communication with shared data in a realtime specification language. At the implementation level, data sharing has obvious performance advantages and is, therefore, often used in current realtime systems. However, there is no apparent advantage in using data sharing at the specification level for describing process interactions at an abstract level. There are instead obvious disadvantages. For example, contention for shared data must be addressed in the specification, which implies that mutual exclusion also must be addressed. Furthermore, future realtime systems are likely to be less tightly-coupled than existing systems. For these reasons, in ASTRAL cooperation is modeled with implicit message passing rather than with data sharing. Implicit rather than explicit message passing was chosen to further simplify the design and to concentrate on the structure of the realtime system. The message passing is also assumed to be instantaneous. The specifics of the implicit multicast message communication model are presented in section 2.2.6.

When designing a realtime specification language one strives to construct models that are both abstract enough to be understandable and yet realistic enough to be useful. The ASTRAL computation model implicitly makes the assumption that there is a global clock and that multicast communication is instantaneous. The assumption of instantaneous broadcasts of state changes is valid if the target implementation uses shared memory, for then there is truly a zero time communication delay. If, however, the implementation is distributed, then this assumption will hold only if the actual delay times are less than the granularity of the timing units. For example, if the communication delay time is in the order of microseconds and the timing requirements are measured in milliseconds, then the delay is a "virtual zero" communication delay. Obviously, as the processes being modeled are more widely distributed the granularity of their critical timing requirements will need to be greater. Thus, to be able to use the ASTRAL approach on a truly distributed system the communication medium for the system must be able to guarantee a "virtual zero" time delay relative to the critical timing requirements. The assumption about a global clock is acceptable for many systems, but may not be valid for some distributed systems. This problem is one that is currently being addressed by a number of researchers [Lam 90, Lis 93, DV 94].

2.2 The ASTRAL Language

In this section the main features of ASTRAL are discussed using an example specification of a phone system composed of multiple control centers. Each control center is responsible for the phones belonging to its area, and it is provided with all the functionality needed to set up a local call. Control centers are also intended to deal with long distance calls (i.e., calls to other areas). Calls to outside areas are modeled by exported variables (i.e., the data is sent to the external environment), while calls from an outside area are modeled as exported transitions (i.e., they are the information provided in the parameters of a call to an exported transition from the external environment). The example is a simplification of a real phone system, every local phone number is seven digits long, area codes are three digits long, a customer can be connected to at most one other phone (either local or in another area), and ongoing calls cannot be interrupted. The motivation for this example came from the telephony example in a paper by Dasarathy [Das 85]. Using Dasarathy's example as a starting point and the local phone system at UC Santa Barbara for further clarification, the example specification was developed.

Most of the examples of the specification that appear in this section are from the global specification and the Central_Control specification. Complete specifications can be found in Appendix A.

2.2.1 Processes

The phone system consists of two process type specifications: Phone, which models the phone instrument found in most homes, and Central_Control.

The process declarations

```
Phones: array[1 .. Num_Phone] of Phone,
Centrals: array[1 .. Num_Area] of Central_Control,
```

which occur in the global specification, declare that there are Num_Phone static instances of the phone process type and Num_Area static instances of the central control process type. Each of these is accessed as Phones[i] (Centrals[i]), where i is in the range 1..Num_Phone (1..Num_Area).

2.2.2 Types

ASTRAL is a strongly typed language. Integer, Real, Boolean, ID, and Time are the only primitive types. All other simple and constructed types used in a process specification must be either declared in the type section of the specification or must be declared in the global specification and explicitly imported by the process type specification.

The following type declarations appear in the global phone system specification.

```
Digit IS TYPEDEF d: Integer (d ≥ 0 & d ≤ 9)
```

indicates a subtype declaration, and

```
Digit_List IS LIST OF Digit
```

declares Digit_List as a list of Digits, while

```
Connection IS STRUCTURE OF (From_Area, From_Number, To_Area, To_Number: Digit_List)
```

declares Connection as a structure composed of four fields of type Digit_List. Connection represents the data structure used to store the information related to a long distance call.

The type ID is one of the primitive types of ASTRAL. Every instance of a process type has a unique id. An instance can refer to its own id by using "Self". There is also an ASTRAL specification function *idtype(i)*, which returns the type of the process that is associated with the id i. Thus the global declaration

```
Phone_ID IS TYPEDEF pid: ID (IDTYPE(pid)=Phone)
```

declares Phone_IDs to be exactly those ids that are for process instances of type Phone.

The central control process specification also defines a new subtype Area_Phone representing the set of phones actually connected to a single phone process instance:

```
Area_Phone IS TYPEDEF p: Phone_ID (In_Area(p) = Self)
```

Finally, the global type declaration

```
Enabled_State IS (Idle, Ready_To_Dial, Dialing, Ringing, Waiting, Talk, Calling, Disconnect,
                  Busy, Alarm)
```

is an enumerated type and indicates the various modes that a customer's phone can be in. These different modes are used to determine what transitions the phone can execute and how the central control should respond to certain actions of a customer's phone.

2.2.3 Variables, Constants, and Definitions

In ASTRAL one state is differentiated from another by the values of the state variables, and it is the state variables that are referenced and/or modified by the state transitions. All of the state variables must be declared in the variable section of the formal specification.

A special variable called Now is used to denote the current time. The value of Now is zero at system initialization time. ASTRAL specifications can refer to the current time (Now) or to an absolute value for time that must be less than or equal to the current time.

In the central control specification there are eight state variables all of which are parameterized by Area_Phone. The first two

```
Phone_State(Area_Phone): Enabled_State,
Long_Distance(Area_Phone): Boolean
```

indicate the central control's view of the mode of each of its customer's phones, and whether or not a phone is involved in a long distance call, respectively.

The reader should note that the central control's view of a particular phone's mode may differ from the actual mode of the phone. For instance, when a customer P first picks up his/her handset the central control may view that particular phone as being idle (i.e., Phone_State(P)=Idle), but it is actually active. The central control, however, will not treat P as active until P's offhook response (i.e., P.Offhook) is processed by the central control's Give_Dial_Tone transition for P. Obviously, this is an action that should occur in a timely fashion. In fact, the global scheduling requirement that is used for the phone system example addresses this issue.

The variables

```
Enabled_Ring_Pulse(Area_Phone), Enabled_Ringback_Pulse(Area_Phone): Boolean
```

are necessary because the central control actually pulses the ring of the callee's phone and the ringback tone of the caller's phone, and they are pulsed independent of each other. When Enabled_Ring_Pulse(P) is true and the mode of phone P is "Ringing", this indicates that phone P should be ringing its bell (i.e., Ring = true for phone P). Note that the central control does not ring the bell, but rather indicates by means of an exported variable (an electronic signal in the actual system) that the bell should be ringing. The transition that actually rings the bell is the Start_Ring transition of process Phone. Enabled_Ringback_Pulse is used in an analogous fashion to pulse the ringback tone in the caller's phone.

The next two variables

```
Connected_To(Area_Phone): Area_Phone,
Number(Area_Phone): Digit_List
```

indicate to what other phone each phone is connected and the number (or partial number) that is being dialed. Connected_To(P) is meaningful only in case of a local call and if P is in waiting, ringing, or talk mode. Likewise, Number(P) is only meaningful when P is in ready to dial or dialing mode.

For long distance calls, the variables

```
LDOut_Line(Area_Phone): Connection,
LDOut_Status(Area_Phone): Connection_Status
```

indicate to whom the phone is connected and the status of the connection. LDOut_Line is not meaningful if Long_Distance is false.

Constants in ASTRAL are values that cannot change over the lifetime of the system. In the global specification, the constant

```
In_Area(Phone_ID): Central_Control_ID
```

is an example of a parameterized constant. It is used to describe that each phone is associated with a unique central control, and that such a binding cannot change.

The first four constants in the central control specification

```
Uptime_Ring, Downtime_Ring, Uptime_Ringback, Downtime_Ringback: Time
```

are of type Time and are used to indicate the pulse rate for ringing a customer's phone and for giving the ringback tone.

In ASTRAL, definitions are used to make the specification more readable. They may contain zero or more parameters. The only definition in the global specification

```
DEFINE
    Plug(L1, L2: Connection):Boolean ==
        L1[From_Area] = L2[To_Area]
```

```
& L1[From_Number] = L2[To_Number]
& L1[To_Area] = L2[From_Area]
& L1[To_Number] = L2[From_Number]
```

is used in the specification of long distance calls to specify the copying of the values of L2 into L1 after having switched the To_Area and To_Number fields with the corresponding From_Area and From_Number fields.

There are two definitions used in the central control specification. The first one

```
Count(P:Area_Phone): Integer == LIST_LEN(Number(P))
```

is used to track how many digits have been processed for each customer. LIST_LEN is an ASTRAL specification function that indicates the number of items in the list.

2.2.4 Interface Section

The interface section of an ASTRAL process specification indicates what types, constants, and definitions declared in the global specification are used by the process, what variables exported by other processes are referenced, and what variables and transitions are exported by the process. These are specified by the Import and Export clauses.

State variables and transitions may be explicitly exported by a process, which makes the variable values and information about the transitions visible to other processes. Exported variables and transitions must be explicitly imported to be referenced in another process specification. Exported transitions are visible to the external environment and are executed in response to calls issued by the external environment.

The export clause for the phone process

```
EXPORT
    Offhook, Next_Digit,
    Pickup, Enter_Digit, Hangup
```

indicates that the values of Offhook and Next_Digit can be imported by other processes and that the transitions Pickup, Enter_Digit, and Hangup are made available to the external environment.

The import clause indicates which globally declared types and constants are used by a process and which variables and transitions exported by other processes are referenced by this process.

The central control specification's import clause

```
IMPORT
    Digit, Digit_List, Connection, Phone_ID, Central_Control_ID, Enabled_State,
    Connection_Status, In_Area, Max_Cust, Plug,
    Phones.Offhook, Phones.Next_Digit, Phones.Pickup, Phones.Enter_Digit
```

indicates the types and constants that are declared in the Phone_System global specification that are imported, as well as the exported variables Offhook and Next_Digit and the exported transitions Pickup and Enter_Digit for each declared instance of process phone.

Figure 2 shows the architecture of a local central control and its associated phones.

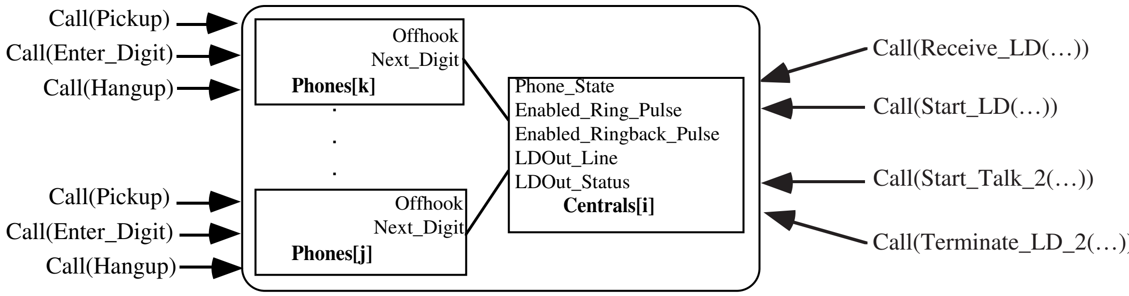


Figure 2: The phone system

2.2.5 Initial Clause

The initial clause of a process specification expresses the restrictions on the initial state of the process type. That is, for each state variable it is necessary to express the restrictions that are to be placed on its initial value.

For the central control the initial condition specifies that, in the view of the central control, initially all phones are idle, no digits have been processed, no phones are ringing nor are any receiving a ringback tone, and no long distance call is ongoing.

```
INITIAL
    FORALL  P:Area_Phone
        (   Phone_State(P) = Idle
        &   Number(P) = NIL
        &   ~Enabled_Ring_Pulse(P)
        &   ~Enabled_Ringback_Pulse(P)
        &   ~Long_Distance(P)
        &   LDOut_Status(P) = Available)
```

It is not necessary to specify an initial value for the Connected variable because it is only meaningful when a phone is in either waiting, ringing, or talk mode. By reviewing the transitions for the central control process one can see that before a phone can be placed in one of these modes its connected value will be updated appropriately (See the Process_Local_Call transition.). Likewise, it is not necessary to specify a value for LDOut_Line if Long_Distance is false.

2.2.6 State Transitions

ASTRAL transitions are used to specify the ways in which an instance of a process type can change from one state to another. A transition is composed of a header, an entry assertion, and an exit assertion. The header gives type information for the transition's parameters and specifies the amount of time required for the transition to execute. The *entry* assertion expresses the enabling conditions that must hold for the transition to occur, and the *exit* assertion specifies the resultant state after the transition occurs. That is, it specifies the values of the state variables in the new state relative to the values they had in the previous state.

In an ASTRAL specification exceptions are dealt with explicitly. That is, a transition can have except/exit pairs in addition to the standard entry/exit pair. An *except* assertion expresses an exception that may occur when a transition is invoked. The corresponding exit assertion specifies the resultant state after the transition occurs.

A transition is executed as soon as its pre-condition is satisfied (assuming no other transition is executing). Whenever a process instance starts executing an exported transition it broadcasts the start time and the values of the actual parameters to all interested processes (i.e., any process that has imported the transition). When the transition is completed the end time as well as the new value of any exported variables that were modified by the transition are broadcast. Of course, any exported variables that are modified by a nonexported transition are also broadcast by the process when the transition completes execution. Thus, if a process is referencing the value of an exported variable while a transition is being executed by the process exporting the variable, the value obtained is the value the variable had when the transition commenced. That is, the ASTRAL computation model views the values of all variables being modified by a transition as being changed by the transition in a single atomic action that occurs when the transition completes execution.

Start(T, t) is a predicate that is true if and only if transition T starts at time t and there is no other time after t and before the current time (Now) when T starts (i.e., t is the time of the last firing of T). For simplicity, the functional notation Start(T) is adopted as a shorthand for "time t such that Start(T, t)" whenever the quantification of the variable t (whether existential or universal) is clear from the context. $Start_k(T)$ is used to give the start time of the kth previous occurrence of T. References to the end time of a transition T may be specified similarly using *End(T)* and $End_k(T)$.

The Process_Local_Call transition represents the central control attempting to establish a connection for a caller who has entered seven digits (i.e., the caller is making a local phone call). It has both a normal entry/exit pair and an except/exit pair. The entry/exit pair corresponds to the case where the called party is in idle mode and the except/exit pair corresponds to the case where the callee is busy. The value Tim3 is the execution time for this transition[2]. Notice that in exit assertions, variable names followed by a prime (') indicate the value that the variable had when the transition fired.

```
TRANSITION  Process_Local_Call(P:Area_Phone)  Tim3
ENTRY
        P.Offhook
    &   ~Long_Distance(P)
    &   Count(P)=7
    &   Phone_State(P)=Dialing
    &   ~Get_ID(Number(P)).Offhook
    &   Phone_State(Get_ID(Number(P)))=Idle
EXIT
        Phone_State(P) = Waiting
    &   Phone_State(Get_ID(Number'(P))) = Ringing
    &   ~Long_Distance(Get_ID(Number'(P)))
```

[2] For simplicity, in this paper it is assumed that the same amount of time is required for executing both the success case of a transition and any exception case. In the actual language design different times are provided for each entry/exit or except/exit pair.

```
     &   Connected(P) = Get_ID(Number'(P))
     &   Connected(Get_ID(Number'(P))) = P
     &   FORALL  P1:Area_Phone
           (    P1≠P  &  P1≠Get_ID(Number'(P))
           →  NOCHANGE(Phone_State(P1))  &  NOCHANGE(Connected(P1)))
EXCEPT
         P.Offhook
     &   ~Long_Distance(P)
     &   Count(P)=7
     &   Phone_State(P)=Dialing
     &   (  Get_ID(Number(P)).Offhook
         |    Phone_State(Get_ID(Number(P)))≠Idle)
EXIT
         Phone_State(P) BECOMES Busy
```

The entry assertion for the success case specifies that the caller's phone must be offhook, the call is not long distance, a seven digit number must have been processed, the phone is in dialing mode, and the phone to be connected to must not be offhook and it must be idle. The exit assertion specifies that the caller's phone is now in waiting mode, the callee's phone is in ringing mode, and the mode for all other phones is unchanged. Furthermore, the caller is indicated as being connected to the callee and vice versa, and the value of connected for all other phones is unchanged. The last conjunct is necessary, because without it the value of the parameterized variables Connected and Phone_State would be undefined for all phones other than the caller and the callee. It should be noted that any variable not mentioned in an unprimed form in the exit clause is assumed to not change. Thus, for the success case the variables LDOut_Line, LDOut_Status, Number, Enabled_Ring_Pulse, and Enabled_Ringback_Pulse do not change. The ASTRAL specification processor automatically generates nochange expressions for these variables when constructing the proof obligations.

The entry assertion for the busy case is identical to the success case except that the phone being called is either not in idle mode or is offhook. The exit assertion for this case indicates that the mode of the caller's phone is now busy and the mode for all other phones is unchanged. The BECOMES operator that is used in this expression is a shorthand provided by ASTRAL for asserting that the value of a parameterized variable changes for some particular argument, but remains unchanged for all of the other arguments. Thus

```
Phone_State(P) BECOMES Busy
```

is equivalent to

```
FORALL  P1:Area_Phone
     (   Phone_State(P1) =
           IF P1=P
           THEN  Busy
           ELSE Phone_State'(P1)
           FI )
```

The Enable_Ring and Disable_Ring transitions are used for modulating the Enabled_Ring_Pulse exported state variable to control the ringing of a customer's phone. The Enable_Ring transition sets this variable to true and the Disable_Ring sets it to false. The Phone process type uses the value of the Enabled_Ring_Pulse variable to determine when to ring its bell. The length of time for the ring pulse to be enabled is determined by the constant Uptime_Ring and the time for it to be disabled is determined by the constant Downtime_Ring.

```
TRANSITION Enable_Ring(P: Area_Phone) Tim4
ENTRY
       ~P.Offhook
    &  Phone_State(P)=Ringing
    &  ~Enabled_Ring_Pulse(P)
    &  FORALL t: Time
       (   End(Disable_Ring(P), t)
       &   FORALL t1 (t ≤ t1 ≤ Now → past(Phone_State(P), t1) = Ringing)
       →   Now - t ≥ Downtime_Ring)
EXIT
       Enabled_Ring_Pulse(P) BECOMES True
```

The entry assertion for the Enable_Ring transition requires that the phone not be offhook, that its mode be ringing, and that the ring pulse is currently disabled. The last conjunct of the entry assertion controls the time between ring pulses. This expression provides an example of the use of the ASTRAL variable Now, which represents the current value of time, and of the last end time of the Disable_Ring transition with parameter value P. It also demonstrates the use of the ASTRAL specification function past, which is used to specify the value that a variable had at some time in the past, that is, past(Phone_State(P), t1) represents the value that variable Phone_State(P) had at time t1. The entry assertion specifies that if there has been a Disable_Ring transition since the phone state became Ringing then it has been at least Downtime_Ring seconds since the last occurrence of the Disable_Ring transition completed execution with parameter P. The reader should note that because Disable_Ring is a transition of the process that is performing the End inquiry, it is not necessary to precede the inquiry with a unique id. The exit assertion for the Enable_Ring transition specifies that the ring pulse for phone P is now enabled.

The Disable_Ring transition works in an analogous manner except that its entry assertion allows for the ring pulse for phone P to be disabled early if phone P is taken offhook.

The invocation of the exported transition Receive_LD by the external environment models the occurrence of an incoming long distance call to a phone connected to the central control. Notice that the entry assertion of the transition requires that the phone not be offhook and that it is idle.

```
TRANSITION Receive_LD(LDIn_Line:Connection) Tim9
ENTRY
       LDIn_Line[To_Area] = Get_Area(Self)
    &  Phone_State(Get_ID(LDIn_Line[To_Number])) = Idle
    &  ~Get_ID(LDIn_Line[To_Number]).Offhook
```

```
EXIT
        Phone_State(Get_ID(LDIn_Line[To_Number])) BECOMES Ringing
     &  LDOut_Status(Get_ID(LDIn_Line[To_Number])) BECOMES Connected
     &  Plug(LDOut_Line(Get_ID(LDIn_Line[To_Number])), LDIn_Line)
     &  FORALL P: Area_Phone
        (P ≠ Get_ID(LDIn_Line[To_Number]) → NOCHANGE(LDOut_Line(P)))
```

LDIn_Line is information provided by the external environment and identifies the local phone process that is about to receive a long distance call. Thus, the conjunct:

```
Plug(LDOut_Line(Get_ID(LDIn_Line[To_Number])), LDIn_Line),
```

which uses the Plug definition imported from the global specification (presented in Section 2.2.3), states that the local central control unit uses the variable LDOut_Line to maintain the data provided by the parameter LDIn_Line.

The last transition to be discussed is the Generate_Alarm transition.

```
TRANSITION Generate_Alarm(P:Area_Phone) Tim14
ENTRY
        P.Offhook
     &  ( Phone_State(P)=Ready_To_Dial
        |  (  Phone_State(P)=Dialing & P.Call(Enter_Digit) < Start(Process_Digit(P))))
     &  (   Count(P)=0 & (Now - End(Give_Dial_Tone(P))) > 30
        |  (   Count(P)>0
          &  (~Long_Distance(P) & Count(P) < 7 | Long_Distance(P) & Count(P)<11)
          &  ((Now - End(Process_Digit(P))) > 20 | (Now - End(Give_Dial_Tone(P))) > 100 ))
EXIT
        Phone_State(P) BECOMES Alarm
```

This transition represents three of the dialing timing requirements that Dasarathy presented in his paper [Das 85]. The restrictions are that

- "After receiving a dial tone, the caller shall dial the first digit within 30 s."
- "After the first digit has been dialed, the second digit shall be dialed no more than 20 s later." and
- "A dialer should dial seven digits in 30 s or less ..."[3]

The first conjunct of the entry assertion for the Generate_Alarm transition requires the phone to be offhook while the second one specifies that the caller is about to begin dialing or in the process of dialing and has not entered a digit since the last digit was processed. The last conjunct captures the three requirements from Dasarathy's paper. The first disjunct specifies that no digits have been processed since the dial tone was enabled (Count(P)=0) and that more than 30 seconds have elapsed since phone P was put in ready to dial mode. The second disjunct specifies that one or more, but less than seven (eleven for long distance), digits have been processed for phone P, and that either it has been more than 20 seconds since the last digit was processed or more than 100 seconds have elapsed since phone P was put in Ready_To_Dial mode. The exit assertion specifies that phone P is put in the alarm mode.

[3] For the example specification the second requirement was extended to cover the time between *any* two digits, and the total dial time was changed to 100 s, which seemed more reasonable.

2.2.7 Environment Clause

Because ASTRAL is intended to be used for designing reactive systems, it is necessary to be able to express assumptions about the external environment in which the system works. This is accomplished by using *environment clauses,* which formalize the assumptions that must hold on the behavior of the environment to guarantee some desired system properties. These assumptions are expressed as first-order formulas involving calls to the exported transitions. If T is an exported transition, *Call(T)* may be used in the environment clause to denote the time of the last occurrence of the call to T (with the same syntactic conventions as Start(T) and End(T)), and $Call_k(T)$ denotes the time of the kth previous occurrence of the call[4].

There are both local and global environment clauses. Local environment clauses refer to a single instance of the process type they are associated with, while the global one refers to the system as a whole.

The local environment clause for the process type Phone is:

```
ENVIRONMENT
      FORALL t: Time (Call(Pickup, t) → ~past(Offhook, t))
   &  FORALL t: Time (Call(Hangup, t) → past(Offhook, t))
   &  FORALL t: Time
         (    Call(Enter_Digit, t)
         →    (  past(Dialtone, t)
              |  EXISTS t1: Time, n: Integer, D: Digit
                   (   2≤ n & Call_n(Enter_Digit(D), t1)
                   &   past(Dialtone, t1) & (n≤ 7 & D ≠1 | n ≤ 11 & D = 1)
                   &   FORALL t2: Time (t1 ≤ t2 ≤ t → past(Offhook, t2))))
   &  FORALL t: Time (Call_2(Pickup, t) → Call(Pickup) - Call_2(Pickup) ≥ 1)
```

This states that the phone must not be offhook in order to pick it up, it must be offhook in order to hang it up, there must be a dialtone in order to dial the first digit or the phone has remained offhook ever since the first digit was dialed, and a customer cannot pick up his/her phone more than twice in a second.

The global environment clause for the phone system specifies that no more than Max_Cust customers connected to the same central control will pick up their phone to initiate a call in any 2 second time period. It is:

```
ENVIRONMENT
   FORALL C: Central_Control_ID
   (SET_SIZE({ SETDEF P: Phone_ID (
                          In_Area(P) = C  &  Now - 2 ≤ P.Call(Pickup) ≤ Now)}) ≤ Max_Cust)
```

2.2.8 Imported variable clause

ASTRAL also allows assumptions about the system context provided by other processes in the system to be expressed in the *imported variable clause*, which describes patterns of changes to the values of imported variables, including timing information about any transitions exported by other processes that may be used by the process being specified

---

[4] Note that there may be a delay from the time a transition T is called until it is actually started.

(e.g., Start(T) and End(T)). The imported variable clause is optional and is not an essential part of an ASTRAL system specification. It is used to aid in proving the correctness of a system in a modular fashion. [CKM 94] provides the details of how this clause is used to partition the correctness proof.

The imported variable clause for the central control process is:

```
SET_SIZE({ SETDEF P: Area_Phone (Now - 2 ≤ P.Start(Pickup) ≤ Now)}) ≤ Max_Cust
```

It states that there are no more than Max_Cust firings of the imported Pickup transitions in any 2 second time period.

2.2.9 Critical Requirements

For a realtime system there are two types of critical requirements: behavioral and temporal. In ASTRAL both types are expressed in the invariants, constraints and schedules.

Invariants and Constraints

The *invariants* express the critical requirements that are to hold in every reachable state. That is, they state properties that must initially be true and must be guaranteed to hold during system evolution. The *constraints* express the critical requirements that must hold between any two states that correspond to the start and end of a transition[5]. Invariants can be global or local; the global invariants represent properties that need to hold for the realtime system as a whole, while local invariants and constraints defined at the process type level represent properties that must hold for each process instance. Invariant and constraint properties must be true regardless of the environment or the context in which the process or system is running.

For the central control process type the invariant clause specifies two restrictions on Count and several on phone modes. The invariant is expressed as follows

```
FORALL  P:  Area_Phone
(     (Long_distance(P) →  Count(P) ≥  0 & Count(P) ≤ 11)
&     (~Long_distance(P) → (  Count(P) ≥ 0 & Count(P) ≤ 7
                               &   (Phone_State(P)=Waiting  →   Phone_State(Connected(P))=Ringing)
                               &   (Phone_State(P)=Ringing  →   Phone_State(Connected(P))=Waiting)
                               &   (Phone_State(P)=Talk  →   Phone_State(Connected(P))=Talk))))
```

The first conjunct of the invariant indicates that for long distance calls the number being dialed by a user can never be more than eleven digits long and that it is always greater than or equal to zero. This invariant demonstrates the use of the definition Count. The second part of the invariant expresses a similar requirement on local calls (the number of digits has to be less than or equal to seven). It also expresses the requirement that when one customer is waiting for another to answer, the other customer's phone is in a ringing state. Similarly if one's phone is ringing then the phone of the caller should be waiting for an answer. Finally, if a phone is in talk mode the phone it is connected to should also be in talk mode.

---

[5] The requirements contained in a constraint could be expressed in an invariant. Thus, the constraint is just a notational convenience.

The only constraint in the central control specification is

```
CONSTRAINT
    FORALL  P:Area_Phone
        (    (Phone_State'(P)=Busy | Phone_State'(P)=Alarm |Phone_State'(P)=Disconnect)
        &   Phone_State(P) ≠ Phone_State'(P)
        →  Phone_State(P)=Idle )
```

This constraint specifies that if a user reaches a busy number, doesn't dial quickly enough and gets into alarm mode, or is disconnected because the other party hangs up the phone, then the only choice for the customer is to hangup (i.e., enter idle mode). Recall that in an ASTRAL expression a primed variable (e.g., x') indicates the value that variable had in the previous state; i.e., when the transition was invoked.

Schedules

Schedules are additional system properties that are required to hold under more restrictive hypotheses than invariants. Like invariants, schedules may be either local or global and obey suitable scope rules in the same style as invariants. Unlike, invariants, however, they express requirements that are to hold provided the environment and system context produce stimuli as prescribed in the environment and imported variables clauses.

Process scheduling clauses deal with timing requirements for that process only. A process schedule cannot prescribe the value of variables for another process. It may refer only to calls to its own exported transitions and references to the values of imported variables from another process.

The schedule clause for the phone process states that transition Pickup fires whenever it is called from the environment:

```
FORALL t: Time (Call(Pickup, t) ↔ Start(Pickup, t))
```

The schedule clause for the central control process consists of seven conjuncts, each of them representing a scheduling requirement. The first one is:

```
FORALL  P:Area_Phone,  t:  Time
    (   Change(P.Offhook,  t)
    &    past(P.Offhook, t)
    &    past(Phone_State(P), t)=Idle
    &    Now - t ≥ MAX(Tim1, …, Tim16) + Max_Cust*Tim1
    → EXISTS  t1:Time
        (t≤t1≤t + MAX(Tim1,…,Tim16) + Max_Cust*Tim1 & past(Start(Give_Dial_Tone(P),t1),t1)))
```

The above scheduling requirement states that if phone P becomes offhook at time t then within MAX(Tim1, …, Tim16) + Max_Cust*Tim1 seconds transition Give_Dial_Tone will fire to serve P. It also shows the use of the ASTRAL predicate Change which is used to denote the last time that a variable has changed its value, that is Change(var, t) is true iff at time t variable var has changed value and there is no other time between t and the current time (Now) in which the variable value has changed .

The six remaining scheduling requirements that compose the schedule clause of the central control specification deal with the pulsing of the Enabled_Ring_Pulse and the Enabled_Ringback_Pulse.

The global schedule clause specifies timing requirements which involve multiple processes. It describes additional properties that the system must satisfy, when all its processes satisfy their own schedules and the assumptions on the behavior of the global environment hold. Only exported variables and the call, start, and end times of exported transitions can be used in the global schedule clause.

The global schedule clause for the example system specifies another of Dasarathy's timing requirements: "The caller shall receive a dialtone no later than 2 s after lifting the phone receiver." The corresponding specification clause is

```
FORALL P:Phone_ID, t: Time
   (    P.Offhook
   &  P.Call(Pickup, t)
   &  Now - t ≥ 2
   &  past(In_Area(P).Phone_State(P),t)=Idle
   →  EXISTS t1:Time (t < t1 ≤ t + 2 & past(In_Area(P).Phone_State(P),t1)=Ready_To_Dial))
```

The first conjunct of the antecedent specifies that phone P is currently offhook. The second and third conjuncts are an example of the use of the Call for a particular instance of the process type phone. They specify that it has been 2 seconds or more since the call of the transition Pickup for phone P. The fourth conjunct specifies that phone P was in idle mode when the Pickup transition was called. This conjunct is necessary because if P was in ringing mode when the receiver was picked up, then the customer should not get a dialtone. The consequent specifies that at some time during the two second period that started with the call of the Pickup transition the mode of phone P (as viewed by the central control) was ready to dial, which enables phone P to execute its Start_Tone transition.

Note that this expression does not specify that phone P actually gets a dialtone, but that it *can* get a dialtone. In order for the global schedule clause to express that phone P gets the dialtone the variable Dialtone would have to be exported by the phone process.

2.2.10 Further Assumptions and Restrictions

Schedules are not required to be proved using the basic elements of the ASTRAL specification. It is important, however, to know that the schedule is feasible. There may be several ways to assure that a schedule is satisfied, such as giving one transition priority over another or making additional assumptions about the environment. Even though this kind of decision should often be postponed until a more detailed design phase, it is important to know that if further restrictions are placed on the specification and/or if further assumptions are made about the environment, then the schedule could be satisfied. For this reason a further assumptions and restrictions clause can be included as part of a process specification. Unlike other components of an ASTRAL specification this clause is only used as guidance to the implementer; it is not a hard requirement.

The *further assumptions and restrictions clause* consists of two parts: a further environment assumptions section and a further process assumptions section. The *further environment assumptions* section obeys the same syntactic rules as the local environment. It states further hypotheses on the admissible behaviors of the environment interacting with the system. A *further process assumptions* section restricts the possible system implementations by specifying suitable selection policies in the case of nondeterministic choice between several enabled transitions, *transition selection*, or by further restricting constants, *constant refinement*. In general, the further process assumptions reduce the level of nondeterminism of the system specification. For more information on the further assumptions and restrictions clause and its role in the proof methodology see [CKM 94].

The further assumptions and restrictions clause for the central control process is:

```
FURTHER ASSUMPTIONS
    CONSTANT REFINEMENT
          2 > MAX(Tim1, …, Tim16) + Max_Cust*Tim1
    TRANSITION SELECTION
       {Give_Dial_Tone, *} TRUE → {Give_Dial_Tone}
```

The above clause states further constraints on the relationship of some constant values and gives transition Give_Dial_Tone priority over the other transitions belonging to the central control process. These assumptions are needed to prove that the process schedule holds, that is, they describe a possible implementation choice that designers can follow to satisfy the critical requirements expressed by the schedule.

3. Composing ASTRAL Specifications

As seen in the previous section, the ASTRAL language contains structuring mechanisms that allow one to build modularized specifications of complex systems. It is often desirable to combine these system specifications into an even more complex system. Consider two ASTRAL specifications: each of these specifications contains one or more process type specifications and a global specification. Composing these specifications means to build a new specification, that is the specification of a system obtained by making the processes of the original specifications interact. The behavior, the environment, and the properties of the new system are obtained from those of its components, once their interaction is formally described. In order to compose ASTRAL specifications one needs to define how to formally describe the interconnection between two or more specifications, how the resulting new specification can be built starting from the specification of its components and the description of their interaction, and under what conditions the properties verified about the components will still be valid in the composed system.

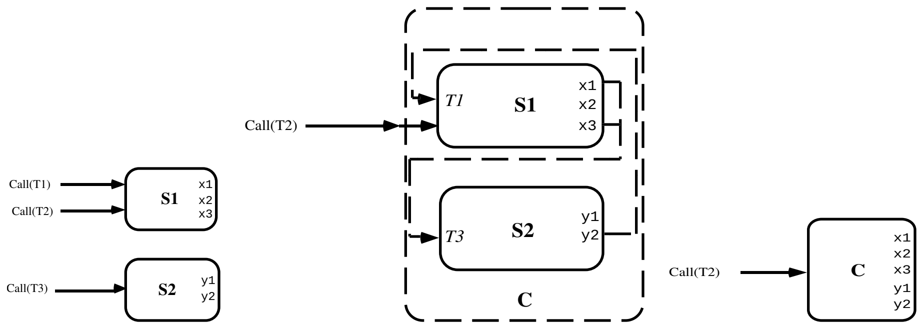
In the next subsection a compose clause, which describes the interaction between two ASTRAL system specifications is introduced. Then, the specification of a long distance network system is introduced, and it is shown how this specification can be composed with the phone system specification to produce the specification of a long distance phone system.

3.1 The Compose Clause

A *compose clause* provides the information needed to compose two or more specifications into a single specification of the combined system. Let S_1 and S_2 denote two ASTRAL top level specifications. The interaction between the processes of S_1 and S_2 is described by specifying which exported transitions of the processes of S_1 (S_2) are no longer exported to the external environment, i.e., the stimuli needed to fire such transitions are produced by a process of the sibling system S_2 (S_1) rather than by the external environment.

Figure 3a shows two systems, S_1 and S_2. S_1 exports transitions T1 and T2 and state variables x1, x2 and x3, while S_2 exports transition T3 and state variables y1 and y2.

When S_1 and S_2 are composed some transitions of S_1 (S_2) will not need an external call, since S_2 (S_1) is now providing part of the environment in which S_1 (S_2) works. For instance, in Figure 3b transitions T1 and T3 are no longer exported since the events that trigger them are now represented by particular values of y2 and x1 and x3, respectively. Thus, the composed system, C, will export only transition T2. That is, the external environment of C can call only transition T2 (See Figure 3c).



a) b) c)

Figure 3: The composition of S_1 and S_2 into C

In general a compose clause contains the following parts:

- A process clause defining how many instances of each process type belonging to S_1 or S_2 are present in the resulting system.
- A set of clauses defining types, constants, and definitions that are used in the compose clause.
- A name clash resolution clause, which is used to solve any possible name clashes that can arise because of overloaded identifiers (i.e., the same identifier is used in both S_1 and S_2 with different meanings).
- A call generation clause which describes how exported transitions of S_1 (S_2) processes are triggered by events occurring in S_2 (S_1) processes. These events are described by formulas of the following form:

FORALL t: Time ,… $(P(S_1) \leftrightarrow \text{Call}(T,t))$,

where $P(S_1)$ is an ASTRAL well formed formula describing the occurrence of the events in S_1 that are equivalent to calling the exported transition T of S_2.

3.2 Long Distance Network

The long distance network specification is composed of a global specification and a single process type specification (Long_Distance_Unit). Each area code is controlled by one process instance of type Long_Distance_Unit. For simplicity, it is assumed that each long distance unit instance is connected with all other instances, so that a direct communication between two long distance unit instances is always possible. The complete long distance network specification can be found in Appendix B.

The global type Line is used to represent the physical lines used for connecting one long distance unit to another and to the external environment.

Long_Distance_Unit has four variables all of which are parameterized by Line:

NetOut(Line), LocOut(Line): Connection,
NetStatus(Line), LocStatus(Line): Connection_Status

NetOut and NetStatus are used to communicate with another long distance unit, while LocOut and LocStatus are exported to send the information about the connection and the status occurring on a given line to the external environment.

The long distance unit process also exports four transitions:

Receive_Local_Req	called whenever a long distance call has been requested from the local area.
Local_Established	called to notify the unit that an incoming call to the local area has been received.
Started_Local_Talk	called to notify the unit that an incoming call, previously received has been answered.
End_Local	called to notify the unit that an incoming call has ended.

Figure 4 shows the interface of the long distance process with the external environment.

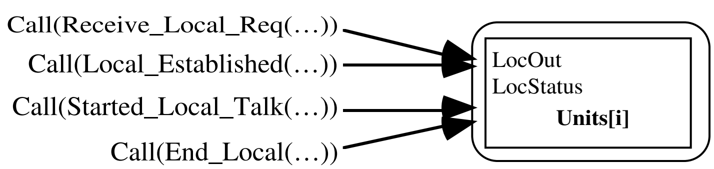


Figure 4: Long_Distance_Unit Interface

The specification of transition Receive_Local_Req is as follows:

```
TRANSITION  Receive_Local_Req(In_Line:Connection)  Ti1
ENTRY
        In_Line[From_Area] = Get_Area(Self)
EXIT
    EXISTS L: Line
        (     NetworkStatus'(L) = Available
        &  Connect(NetworkOut(L), In_Line)
        &  FORALL L1:Line (L1 ≠ L → NOCHANGE(NetworkOut(L1))
        &  NetworkStatus(L) BECOMES In_Progress)
```

A complete discussion of the specification can be found in [CK 93].

3.3 Composition Example

In this section the phone system specification is composed with the long distance network to obtain the specification of a long distance phone system. This requires the introduction of a compose section to define how the composition is carried out:

```
COMPOSITION OF Phone_System, Long_Distance_Network AS Phone_Network
```

The compose section contains the declaration of the process type instances composing the new system:

```
PROCESSES
    Phones: array[1 .. Num_Phone] of Phone,
    Centrals: array[1 .. Num_Area] of Central_Control
    Units: array[1 .. Num_Area] of Long_Distance_Unit
```

It also contains the declaration of constant LD_Unit which defines the association of every Central_Control process instance with its corresponding Long_Distance_Unit process instance.

```
CONSTANTS
    LD_Unit(Central_Control_ID): LDU_ID
```

In order to specify that each long distance unit is associated with a single central control, the compose section contains the following axiom:

```
AXIOM
    FORALL C1, C2: Central_Control_ID (LD_Unit(C1) = LD_Unit(C2) → C1 = C2)
```

Finally, the compose section describes how events occurring in the central control process instances are equivalent to calling the exported transitions of the long distance unit process instances and vice versa. As an example, long distance unit transition Receive_Local_Req for process instance LD_Unit(In_Area(P)) is triggered every time a customer P dials a long distance number; that is, whenever the status of the incoming line from a central control process instance (In_Area(P).LD_Out_Status) becomes "In_Progress":

```
FORALL t: Time, P: Phone_ID
    (  Change(In_Area(P).LDOut_Status(P),t) & In_Area(P).LDOut_Status(P) = In_Progress
    ↔  LD_Unit(In_Area(P)).Call(Receive_Local_Req(In_Area(P).LDOut_Line(P)),t))
```

In a similar manner, the central control transition Receive_LD is triggered every time an incoming long distance call is detected by a long distance unit. That is, the status of the outgoing line from a long distance unit (LD_Unit(C).Local_Status) becomes "In_Progress":

```
FORALL t: Time, C: Central_Control_ID, L: Line
    (  Change(LD_Unit(C).LocStatus(L),t) & LD_Unit(C).LocStatus(L) = In_Progress
    ↔  C.Call(Receive_LD(LD_Unit(C).LocalOut(L)),t))
```

Figure 5 shows how the variables and transitions from the phone system and the long distance network system interact in the composed system (For simplicity, the exported items of the phone process are not depicted). The complete composition section is presented in Appendix C.

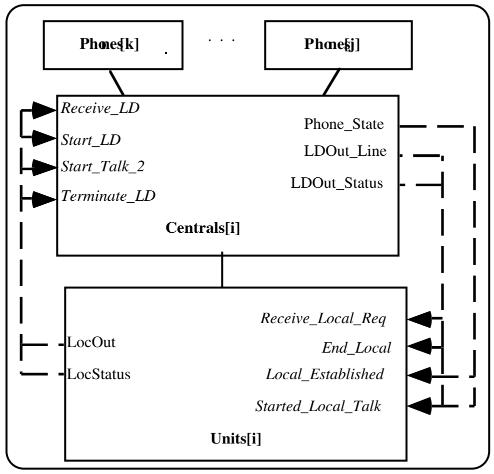


Figure 5: The composed system

As a result of the composition, the above transitions are no longer exported and their ENTRY/EXIT pair is extended to include the triggering mechanism. For example, transition Receive_Local_Req becomes (the italic part is what has been added):

TRANSITION Receive_Local_Req Ti1
ENTRY
EXISTS t: Time, P: Phone_ID
(Change(In_Area(P).LDOut_Status(P),t) & In_Area(P).LDOut_Status(P) = In_Progress
& LD_Unit(In_Area(P)) = Self & Start(Receive_Local_Req) < t)
EXIT
EXISTS t: Time, P: Phone_ID
(Change(In_Area(P).LDOut_Status'(P),t) & In_Area(P).LDOut_Status'(P) = In_Progress
& LD_Unit(In_Area(P)) = Self & $Start_2$(Receive_Local_Req) < t
& EXISTS L: Line
(NetStatus'(L) = Available
& Connect(NetOut'(L), In_Area(P).LDOut_Line'(P))
& NetStatus(L) BECOMES In_Progress
& FORALL L1:Line (L1 $\neq$ L $\rightarrow$ NOCHANGE(NetOut(L1)))))

3.4 Automatic Generation of Composed Specification

When composing two or more system specifications using the compose clause it is desirable to produce the specification of the composed system. Since an ASTRAL specification is composed of a global specification and a set of process type specification, this means that it is necessary to build the new global specification, and the new process specifications using the compose clause.

The new global specification contains a set of clauses defining types, constants and definitions built by taking the corresponding clauses declared in the compose clause and those belonging to both of the global specifications and using the name clash clause to resolve any name clashes.

Every process type specification in both of the systems is included in the composed system; however, the following transformations are needed:

- The import/export clause of each process type is modified since some transitions are no longer exported and some state variables are now imported instead. As a consequence both the local environment clause and the imported variables clause are modified in order to account for the no longer exported transition and the newly imported variables, respectively;

- Each transition belonging to a process type referred to in the call generation clause of the compose section, is modified using the related call generation clause.
- The local schedule is modified using the related call generation clause if it refers to the call of a no longer exported transition.

Notice that the local invariant and the further process assumptions are not modified.

This composition can be constructed automatically. The details of how to construct the composite specifications can be found in [CK 93].

4. Status of the ASTRAL Software Development Environment

In order to get designers to use formal methods to develop realtime systems it is necessary to provide them with an integrated set of tools for writing and analyzing their specifications. The ASTRAL Software Development Environment is intended to be an integrated set of design and analysis tools based on the ASTRAL formal framework. The tools that make up the support environment are a syntax-directed editor, a specification processor, a mechanical theorem prover, a specification testing component, and a browser kit.

The approach that was taken in building the ASTRAL software development environment was to first build an executive that integrates all of the component tools. This executive provides the user with a graphical user interface running under Unix with X-windows System 11 Release 5 with Motif. It includes extensive context-sensitive help facilities and the necessary optional features to get the level of guidance needed by a novice user while not hindering the experienced specifier. The system provides navigation windows, which allow the user to navigate through the specification in a hierarchical manner. A key design criteria for the environment was that the user should never need to switch between tools nor should there be any need for data exchange via temporary files. That is, the system is intended to be a fully integrated environment in which the user could change from specification writing to type checking to generating proof obligations with a mere button push. In its current state the software development environment contains stubs for the tools that are not yet ready to be integrated into the environment. Each of the component tools and their current status are discussed in the following subsections.

4.1 Syntax-Directed Editor

The ASTRAL syntax-directed editor aids the designer in constructing ASTRAL formal specifications. With this editor a user can build the specification in any order desired. When the user enters a specification component the syntax is automatically checked. Figure 6 is a screen dump showing the highest level navigation window for the phone system specification of Appendix A.

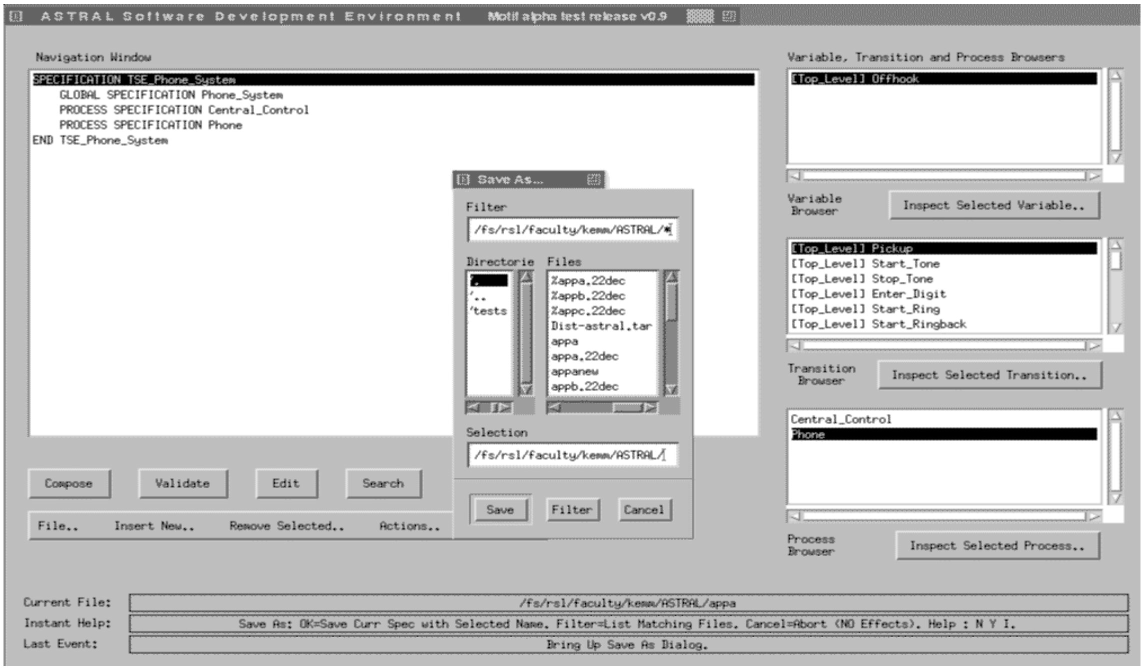


Figure 6: Screen Dump of Initial Navigation Window

At this level the user can see that there are two different process type specifications, in addition to the global specification. It also shows a popup window for saving the current specification and the help line explains the options. The screen dump in Figure 7 is the result of hierarchically navigating through the phone process and top level navigation windows and finally creating the Enter_Digit transition by selecting "transition" off the "Insert New" menu and then editing the newly created transition. The edit popup window has been selected to edit the exit assertion of the transition.

4.2 Specification Processor

The specification processor consists of a validation component and a verification condition generator (i.e., proof obligation generator). Because the user is allowed to enter the specification in any order, it is not always reasonable to perform all type checking immediately. Therefore, the user controls when the type checking is to be done. He/she can choose to type check the entire specification at any time by selecting the "Validate" button, which can be seen to the left of the bottom of the popup window in Figure 6.

The proof obligation generator component of the specification processor generates the necessary proof obligations to assure that each process specification is consistent with its invariants, constraints, and schedules, and that the properties of the collection of state machine specifications for the processes of the system is sufficient to assure the global invariant for the system and in some cases also the global scheduling constraints. These are known as the *intra-level* proof obligations. This tool also generates the necessary proof obligations to assure that a less abstract lower level specification for a process is a correct implementation of the parent specification that it implements. These are the *inter-level* proof obligations. The proof theories for both the intra-level and the inter-level proofs are defined in [CKM 94, CKM 95]. The proof obligations are generated by clicking on the "Actions" button, which can also be seen to the left of the bottom of the popup window in Figure 6, and choosing either intra-level or inter-level proof obligations. Because the theorem prover component has not yet been integrated in the environment, the resulting proof obligations are currently written to a file.

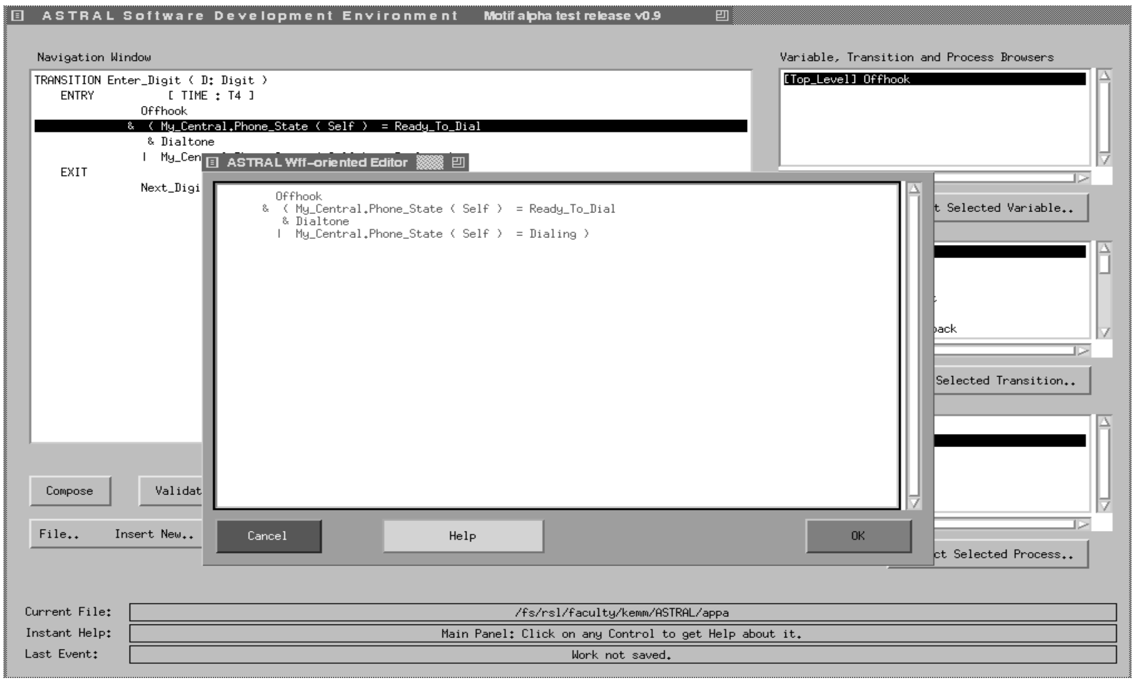


Figure 7: Screen Dump of Enter_Digit Navigation Window

4.3 Theorem Prover

A mechanical theorem prover component to discharge the proof obligations generated by the specification processor will also be integrated into the software development environment. However, it has been the experience of the Reliable Software Group that it is more efficient to build or adapt an existing theorem prover after one knows the types of theorems that need to be proved. For instance, when ASLAN was used in the MCC's Spectra software development environment [GBG 90, Ger 93] both the HOL [Gor 87] and Boyer and Moore [BM 90] theorem provers were adapted to prove the proof obligations that were generated by the ASLAN specification processor. More recently, the ASLAN specification processor was coupled to the Otter theorem prover [WM 92], which was developed at Argonne National Laboratory. Based on this experience, the integration of a theorem prover is being delayed until a reasonable number of ASTRAL specifications have been written and the corresponding proof obligations have been generated. At that time the proof obligations can be analyzed to determine what existing theorem prover(s) would be best to use.

4.4 Specification Testing Tool

In order to reduce the cost of developing reliable systems that also provide the desired functionality, it is necessary to provide a means to test the formal specifications early in the software life cycle. As was mentioned in the introduction, a scheme for translating ASTRAL formal specifications to TRIO was defined for an earlier version of the specification language. To test the feasibility of this approach a simple example specification that modeled a traffic light and the traffic on two intersecting streets was used. The complete specification was manually translated and the resulting specification was tested using the TRIO history checker, which was developed at the Politecnico di Milano [FM 94]. When testing the specification several problems with the ASTRAL specification, which revealed the potential for a traffic accident with the system as specified, were discovered. This experience lead to the decision to include an ASTRAL to TRIO translator and the TRIO-based history checkers as components of the software development environment.

However, now that a formal semantics for ASTRAL has been defined, the decision has been made to build on the Reliable Software Group's experience with directly executing formal specification languages symbolically. This experience includes implementing a symbolic execution tool for testing ASLAN specifications [DK 94], which is called Aslantest. This tool provides designers and users with a flexible means of animating system specifications to test for various functional requirements. The Reliable Software group has also designed and implemented a symbolic executor, called CASEX, for a verifiable subset of Ada, which includes tasking [HK 88]. This tool uses the interleaving approach, where the execution of component tasks are interleaved to model their concurrent execution. These tools served as a basis for the ASTRAL specification testing component, which is currently being designed.

4.5 Browsers

Finally, the software development environment contains three databases for analyzing inter-process and inter-transition relationships. These databases store information about variables, transitions, and processes of the current specification, and they are automatically updated and kept consistent every time the user edits anything in the ASTRAL specification. There are browsers associated with each of these databases and each of them has a dedicated window and a query button, which can be seen to the right of the navigation window in Figure 6. These browsers help the user to quickly determine what variables, transitions, or processes are affected by a change to some existing variable or transition. It is expected that the browsers will be very useful during the maintenance phase when the specifications are being modified.

5. Related Work

ASTRAL is an outgrowth of the authors' previous work on realtime formal specification languages. The Reliable Software Group at UCSB had already developed a layered formal specification language for sequential systems. This formal specification language, as well as the specification language processor, is called ASLAN. ASLAN's strengths include layered refinement, a state machine process model, and the ability to specify non-timing requirements and behavior. An overview of the ASLAN language can be found in [AK 86a, AK 86b], and further information and use of the language processor are detailed in the ASLAN User's Manual [AK 85]. ASTRAL builds on ASLAN by introducing time to the nondeterministic state machine modeling style of ASLAN, where states are specified via predicates, and state changes occur as a consequence of the application of atomic operations. Modularity and hierarchy of specifications are also inherited from ASLAN, and the syntactic flavor of ASLAN is retained.

RT-ASLAN is an earlier extension of ASLAN for specifying realtime systems [AK 86b]. In RT-ASLAN a system is modeled by a collection of state machine specifications. Processes are represented by communicating subspecifications, and shared data interfaces are represented by interface subspecifications. Each communicating subspecification defines the local state variables, state transitions and critical requirements of a single process. Each interface subspecification is essentially a data object protected by a monitor. The experience gained from specifying timing properties using RT-ASLAN were useful in designing the ASTRAL approach. The RT-ASLAN data sharing approach for modeling process interaction, however, was determined to be unsatisfactory for ASTRAL.

TRIO is a logic language designed at the Politecnico di Milano as a formal notation for specifying and verifying timing requirements [GMM 90, MMP 96]. The research and experimentation on TRIO addressed the issue of executing TRIO specifications. The language, however, lacks many of the qualities that would make it a practical language for specifying real world systems. It is hard to read and understand; there are no mechanisms for modularizing a complex specification nor for arranging it as a hierarchy of abstraction levels. Due to these weaknesses, TRIO appears more like a realtime machine level formal language than a language to be used by a system specifier. For this reason it was decided to build a high level language that could be translated to TRIO.

Although the ASTRAL language was based on the authors' experience with ASLAN and TRIO, it was developed as a new language. The ASLAN state machine approach with layering is retained, but ASTRAL uses a novel approach to modeling interprocess communication, and many new specification ideas are introduced for expressing interaction with the environment and timing relationships. The experience of basing the ASTRAL language on the ASLAN and TRIO approaches prompted the selection of the name for the language: an ASlan based TRio Assertion Language.

Several different approaches to formal specification of realtime systems can be found in literature. Among them:

- Operational approaches based on different kinds of automata, including extensions to finite state machines, such as Statecharts [Har 87, HLN 88], Modecharts [JM 94], different kinds of timed automata [AD 91, AFH 91] and various kinds of high level Petri nets, such as [MF 76] and [GMM 89].
- Formalism based on temporal logics such as [JM 86, KR 85, KKZ 87, Koy 89, JL 89] and previous work on temporal logic [Pnu 81, Ost 89].

- Extensions to algebraic based languages like CCS [Mil 83] such as [Wan 90] and Constrained Expressions [DAW 88].

In [AD 91] timed automata are used both for specifying the system and describing its properties. Thus, the problem of verifying whether a system satisfies a given property is reduced to the problem of checking the emptiness of the intersection between the languages accepted by the automata representing the system and the one describing the property respectively[6]. [AFH 91] shows how to translate formulas written in the MITL temporal logic into timed automata. This approach allows one to check the correctness of a system modeled by timed automata against critical requirements expressed as MITL formulas. ASTRAL, instead allows one to prove that a system meets its critical requirements by means of a proof system, that is by providing an axiomatization of the behavior of the ASTRAL abstract machine. Moreover, timed automaton is a low level formalism when compared to ASTRAL.

An approach similar to ASTRAL's is presented in [AL 91] where Abadi and Lamport show how TLA can be used to specify realtime systems. A TLA specification is a formula that describes the set of allowed behaviors of the system. The formula refers to a set of variables that can be viewed as the system state variables. Properties of the system are also expressed by TLA formulas and therefore in order to show that a given specification satisfies a given property one must prove that the former formula implies the latter. More recently, in [AL 95] Abadi and Lamport show how to specify a system as a conjunction of the specifications of its components. As is the case with ASTRAL, properties of the system as a whole are proved by reasoning about the components. Furthermore, their presentation of conditional implementations where certain assumptions are made is similar to ASTRAL's use of environment clauses and imported variable clauses. The ASTRAL approach differs, however, in that invariants that depend on outside assumptions to be maintained are separated from those that don't (i.e., the distinction between invariants and schedules in ASTRAL).

ASTRAL also inherits some features from synchronous languages, such as ESTEREL [BS 91], LUSTRE [HCR 91, HLR 92], and SIGNAL [GGB 91]. These languages describe programs that react instantaneously to external events. The former is an imperative language, providing assignments, conditionals, loops, etc. The latter two are dataflow languages. For example, ESTEREL's intermodule communication via signals transferred in an instantaneous broadcast network is mirrored by ASTRAL's interprocess communication. ASTRAL differs from these languages, however, in that the actions performed by the system in response to external stimuli take a nonnull time (i.e., there is a delay between external events and responses). Thus, ASTRAL's model is asynchronous, whereas ESTEREL, LUSTRE, and SIGNAL are synchronous. In the case of LUSTRE, validation of specifications is supported by model checking.

Like ASTRAL, the work of Gerber and Lee [GL 92] provides a layered approach to the verification of realtime systems. With their approach the CSR application language is used to specify processes, and these processes are mapped to system resources using a

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[6] Actually the interesection is between the language accepted by the automata representing the system and the one accepted by the complement of the automata representing the property.

configuration schema. A CSSR specification is then automatically generated. This approach is similar to the ASTRAL to TRIO translation; although, their approach is much more operational than the ASTRAL/TRIO approach.

Another language supporting layered specifications is HMS [GF 91]. However the HMS notion of multilevel specifications is quite different from ASTRAL's. In HMS higher level specifications impose constraints on lower levels; the final specification is therefore composed of all levels. In ASTRAL each level is shown to be a correct refinement of the corresponding upper level; as a consequence the lowest level constitutes the final specification.

Recently, a number of approaches have been proposed to build formal proofs for realtime systems [ACD 90, FMM 94, GF 91, HL 94, JM 94, LRD 95, Ost 89, Suz 90]. In most cases, they are based on low level formalisms, i.e., abstract machines and/or assertion languages that are not provided with modularization and abstraction mechanisms. As a consequence, the proofs lack structure, which makes them unsuitable for dealing with complex real-life systems. In contrast, ASTRAL is provided with structuring mechanisms that allow one to build modularized specifications of complex systems with layering. As a result, one of the distinguishing feature of ASTRAL is that formal proofs are also structured [CKM 94, CKM 95].

6. Conclusions and Future Work

This paper introduces ASTRAL, a new formal specification language for realtime systems. The language is an outgrowth of the authors' previous work on realtime formal specification languages.

ASTRAL was designed to support good software engineering practice. The structuring mechanisms that allow one to build modularized specifications of complex systems with layering are an example of this. This modular separation of processes allows for a better understanding of the system design by being able to consider each component separately. It also provides the lead designer with reasonable units to be assigned to different design teams. The modular approach also simplifies the proof process by allowing the process properties to be proved independently and then using these properties to prove the properties of the total system, as expressed in the global specification. The layering also allows the proof of the implementation of a process to be simplified.

ASTRAL also supports good software engineering practice by having both invariants and schedules, which contributes to the reuse of process specifications. That is, because properties expressed in the invariant are guaranteed to hold for the process, regardless of what environment it runs in, the process can be reused in any system design that requires only the properties expressed in the invariant. If in addition the properties expressed in the schedule were necessary, then the system for which the process was being considered would have to assure that the environment and imported variables properties were also satisfied. By splitting the environment dependent properties from the environment independent properties processes are likely to be reused more than if they were grouped together.

Another feature of the language that supports good software engineering practice is the further assumptions clause. By including this clause the schedule requirements can be proved to be satisfiable without requiring the specifier to include implementation details that are inappropriate for the more abstract level of design. This avoids the common problem of over specifying a system in the early stages of design. In addition, by including more than one further assumptions clause the designer can document several possible implementation approaches in the higher level design.

This paper also describes how to compose two or more ASTRAL system specifications into a more complex realtime system. To accomplish this a compose clause was added to the basic specification language. It was also demonstrated how the compose clause can be used to transform two or more existing system specifications into a new specification for the composite system. This too contributes to reuse.

ASTRAL has been used to specify a number of interesting realtime systems. In [CKM 94] the results of using it to formally specify a CCITT system that consists of a packet assembler process and several input processes is reported. The use of ASTRAL as a hardware description language was demonstrated in [BCF 91]. In that paper it was used to formally specify a checksum generator and a universal asynchronous receiver transmitter (UART) between a modem and a microprocessor. The first of these examples had four distinct process types and the second had six. At Delft University of Technology (The Netherlands) ASTRAL was used to specify a robot control system [BBK 95]. These case studies as well as the phone system example presented in this paper demonstrate the expressiveness and the power of the language. They also show ASTRAL's usefulness for specifying varying types of realtime systems from basic hardware to complete communication systems.

Future work will proceed in several directions. One direction is to experiment further with the ASTRAL approach in more complex real life cases. Although the case studies have shown that the language is highly expressive and powerful, more experimentation is needed to further assess the approach.

Another research direction deals with completing the implementation of the software development environment.

A third research direction consists of enhancing and extending the theory behind the approach. The relationship between the target physical architecture and the ASTRAL computation model needs to be examined more closely. Which assumptions need to be relaxed or modified in order to fit target architectures more closely? A typical example is the assumption that as soon as a task terminates a transition, the changed values of the exported variables are immediately visible to all other tasks. Another assumption of the computation model that needs to be addressed is the global clock.

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Appendix A The Phone System Specification

```
GLOBAL SPECIFICATION Phone_System

PROCESSES
    Phones: array[1 .. Num_Phone] of Phone,
    Centrals: array[1 .. Num_Area] of Central_Control

TYPE
    Positive_Integer IS TYPEDEF p:Integer (p > 0),
    Digit IS TYPEDEF d: Integer (d ≥ 0 & d ≤ 9),
    Digit_List IS LIST OF Digit,
    Connection IS STRUCTURE OF (From_Area, From_Number, To_Area, To_Number: Digit_List),
    Phone_ID IS TYPEDEF pid: ID (IDTYPE(pid)=Phone),
    Central_Control_ID IS TYPEDEF pid: ID (IDTYPE(pid)=Central_Control),
    Enabled_State IS (Idle, Ready_To_Dial, Dialing, Ringing, Waiting, Talk, Calling, Disconnect, Busy, Alarm),
    Connection_Status IS (Available, In_Progress, Disconnected, Connected, Talking)

CONSTANT
    In_Area(Phone_ID): Central_Control_ID,
    Max_Cust, Num_Phone, Num_Area : Positive_Integer

DEFINE
    Plug(L1, L2: Connection):Boolean ==
            L1[From_Area] = L2[To_Area]
        &   L1[From_Number] = L2[To_Number]
        &   L1[To_Area] = L2[From_Area]
        &   L1[To_Number] = L2[From_Number]

ENVIRONMENT
    FORALL C: Central_Control_ID
        (SET_SIZE({ SETDEF P: Phone_ID (In_Area(P) = C & Now - 2 ≤ P.Call(Pickup) ≤ Now)} ) ≤ Max_Cust)

SCHEDULE
    FORALL P:Phone_ID, t: Time
        (   P.Offhook
        &   P.Call(Pickup, t)
        &   Now - t ≥ 2
        &   past(In_Area(P).Phone_State(P), t) = Idle
        →   EXISTS t1:Time (t < t1 ≤ t + 2 & past(In_Area(P).Phone_State(P), t1) = Ready_To_Dial))

END Phone_System
```

```
SPECIFICATION Phone
LEVEL Top_Level

IMPORT
    Digit, Phone_ID, Central_Control_ID, Enabled_State, In_Area,
    Centrals.Phone_State, Centrals.Enabled_Ring_Pulse, Centrals.Enabled_Ringback_Pulse

EXPORT
    Offhook, Next_Digit, Pickup, Enter_Digit, Hangup

CONSTANT
    T1,T2,T3,T4,T5,T6,T7,T8,T9,T10,T11: Time

VARIABLE
    Offhook,Dialtone,Ring,Ringback,Busytone: Boolean,
    Next_Digit: Digit
```

```
DEFINE
    My_Central: Central_Control_ID == In_Area(Self)

ENVIRONMENT
        FORALL t: Time (Call(Pickup, t) → ~past(Offhook, t))
    &   FORALL t: Time (Call(Hangup, t) → past(Offhook, t))
    &   FORALL t: Time
        (   Call(Enter_Digit, t)
        → (   past(Dialtone, t)
            |   EXISTS t1: Time, n: Integer, D: Digit
                (   2 ≤ n & Call_n(Enter_Digit(D), t1)
                &   past(Dialtone, t1) & (n ≤ 7 & D ≠ 1 | n ≤ 11 & D = 1)
                &   FORALL t2: Time (t1 ≤ t2 ≤ t → past(Offhook, t2)))))
    &   FORALL t: Time (Call_2(Pickup, t) → Call(Pickup) - Call_2(Pickup) ≥ 1)


INITIAL
        ~Offhook & ~Dialtone & ~Busytone & ~Ring & ~Ringback


INVARIANT
        (Dialtone → ~Ring & ~Ringback & ~Busytone)
    &   (Ring →  ~Dialtone & ~Ringback & ~Busytone)
    &   (Ringback →  ~Dialtone & ~Ring & ~Busytone)
    &   (Busytone →  ~Dialtone & ~Ring & ~Ringback)

SCHEDULE
    FORALL t: Time (Call(Pickup, t) ↔ Start(Pickup, t))


TRANSITION Pickup    T1
ENTRY
        ~Offhook
EXIT
        Offhook

TRANSITION Start_Tone   T2
ENTRY
        Offhook
    &   My_Central.Phone_State(Self)=Ready_To_Dial
    &   ~Dialtone
EXIT
        Dialtone

TRANSITION Stop_Tone   T3
ENTRY
        Offhook
    &   My_Central.Phone_State(Self)=Dialing
    &   Dialtone
EXIT
        ~Dialtone

TRANSITION Enter_Digit(D:Digit) T4
ENTRY
        Offhook
    &   (   My_Central.Phone_State(Self)=Ready_To_Dial
            &  Dialtone
        |   My_Central.Phone_State(Self)=Dialing)
EXIT
        Next_Digit=D
```

```
TRANSITION Start_Ring   T5
ENTRY
        ~Offhook
    &  My_Central.Phone_State(Self)=Ringing
    &  My_Central.Enabled_Ring_Pulse(Self)
    &  ~Ring
EXIT
        Ring

TRANSITION Stop_Ring   T6
ENTRY
        Ring
    &  ~My_Central.Enabled_Ring_Pulse(Self)
EXIT
    ~Ring

TRANSITION Start_Ringback T7
ENTRY
        Offhook & ~Ringback
    &  My_Central.Phone_State(Self)=Waiting
    &  My_Central.Enabled_Ringback_Pulse(Self)
EXIT
    Ringback

TRANSITION Stop_Ringback T8
ENTRY
        Ringback
    &  ~My_Central.Enabled_Ringback_Pulse(Self)
EXIT
        ~Ringback

TRANSITION Start_Busytone T9
ENTRY
        Offhook
    &  My_Central.Phone_State(Self)=Busy
    &  ~Busytone
EXIT
        Busytone

TRANSITION Stop_Busytone T10
ENTRY
        Busytone
    &  My_Central.Phone_State(Self)≠Busy
EXIT
        ~Busytone

TRANSITION Hangup   T11
ENTRY
        Offhook
EXIT
        ~Offhook


END Top_Level
END Phone
```

```
SPECIFICATION Central_Control
LEVEL Top_Level

IMPORT
    Digit, Digit_List, Connection, Phone_ID, Central_Control_ID, Enabled_State, Connection_Status,
    In_Area, Max_Cust, Plug, Phones.Offhook, Phones.Next_Digit, Phones.Pickup, Phones.Enter_Digit

EXPORT
    Phone_State, Enabled_Ring_Pulse, Enabled_Ringback_Pulse, LDOut_Line, LDOut_Status,
    Receive_LD, Start_LD, Start_Talk_2, Terminate_LD_2

TYPE
    Area_Phone IS TYPEDEF p: Phone_ID (In_Area(p) = Self)

VARIABLE
    Phone_State(Area_Phone): Enabled_State,
    Long_Distance(Area_Phone): Boolean,
    Enabled_Ring_Pulse(Area_Phone), Enabled_Ringback_Pulse(Area_Phone): Boolean,
    Connected_To(Area_Phone): Area_Phone,
    Number(Area_Phone): Digit_List,
    LDOut_Line(Area_Phone): Connection,
    LDOut_Status(Area_Phone): Connection_Status

DEFINE
    Count(P: Area_Phone): Integer == LIST_LEN(Number(P)),
    Calling_Out(P: Area_Phone, L: Connection):Boolean ==
            P.Offhook
        &   Long_Distance(P)
        &   Get_Area(Self) = L[To_Area]
        &   Get_Number(P) = L[To_Number]
        &   Plug(LDOut_Line(P), L)

CONSTANT
    Uptime_Ring, Downtime_Ring, Uptime_Ringback, Downtime_Ringback, LD_Timeout, Delta: Time,
    Tim1,Tim2,Tim3,Tim4,Tim5,Tim6,Tim7,Tim8,Tim9,Tim10, Tim11, Tim12, Tim13, Tim14, Tim15, Tim16: Time,
    Get_ID(Digit_List): Area_Phone,
    Get_Number(Area_Phone), Get_Area(Central_Control_ID), Pick_Area(Digit_List), Pick_Number(Digit_list): Digit_List

ENVIRONMENT
    FORALL t: Time, L: Connection
    (   Call(Terminate_LD_Call_2(L), t)
    → EXISTS t1: Time, LS: Connection_Status (t1 < t & (Call(Receive_LD(L), t1) | Call(Start_LD(L,LS), t1))))

&   FORALL t:Time, L:Connection
    (Call(Start_Talk_2(L),t) → EXISTS t1:Time, LS: Connection_Status (t1 < t & Call(Start_LD(L,LS),t1)))

&   FORALL t: Time, L: Connection, LS: Connection_Status
    (   Call(Start_LD(L,LS), t)
    → EXISTS t1: Time, P: Area_Phone (t1 < t & Start(Connect_Long_Distance(P), t1) & past(Calling(P, L), t)))

&   FORALL t: Time (Call2(Receive_LD, t) → Call(Receive_LD) -  t > LD_Timeout)

IMPORTED VARIABLE CLAUSE
    SET_SIZE( { SETDEF P: Area_Phone (Now - 2 ≤ P.Start(Pickup) ≤ Now)} ) ≤ Max_Cust

INITIAL
    FORALL P:Area_Phone
        (   Phone_State(P) = Idle
        &   Number(P) = NIL
        &   ~Enabled_Ring_Pulse(P)
        &   ~Enabled_Ringback_Pulse(P)
        &   ~Long_Distance(P)
        &   LDOut_Status(P) = Available)
```

INVARIANT
FORALL P:Area_Phone
((Long_Distance(P) $\rightarrow$ Count(P) $\geq$ 0 & Count(P) $\leq$ 11)
& (~Long_Distance(P) $\rightarrow$ (Count(P) $\geq$ 0 & Count(P) $\leq$ 7
& (Phone_State(P)=Waiting $\rightarrow$ Phone_State(Connected_To(P))=Ringing)
& (Phone_State(P)=Ringing $\rightarrow$ Phone_State(Connected_To(P))=Waiting)
& (Phone_State(P)=Talk $\rightarrow$ Phone_State(Connected_To(P))=Talk))))

CONSTRAINT
FORALL P: Area_Phone
((Phone_State'(P)=Busy | Phone_State'(P)=Alarm | Phone_State'(P)=Disconnect)
& Phone_State(P) $\neq$ Phone_State'(P)
$\rightarrow$ Phone_State(P)=Idle)

SCHEDULE
FORALL P:Area_Phone, t: Time
(Change(P.Offhook, t) & past(P.Offhook, t)
& past(Phone_State(P), t)=Idle
& Now - t $\geq$ MAX(Tim1, …, Tim16) + Max_Cust*Tim1
$\rightarrow$ EXISTS t1:Time (t $\leq$ t1 $\leq$ t + MAX(Tim1, …, Tim16) + Max_Cust*Tim1 & past(Start(Give_Dial_Tone(P)),t1) = t1))

& FORALL P:Area_Phone
(Phone_State(P)=Ringing
& Now - Change(Phone_State(P))$\geq$ Downtime_Ring
$\rightarrow$ EXISTS n: Integer
(End_n(Enable_Ring(P)) > Change(Phone_State(P))
& End_n(Enable_Ring(P)) $\leq$ Change(Phone_State(P)) + Downtime_Ring))

& FORALL P: Area_Phone
(Phone_State(P)=Ringing
& End(Enable_Ring(P)) > Change(Phone_State(P))
& Now $\geq$ End(Enable_Ring(P)) + Uptime_Ring + Delta
$\rightarrow$ End(Disable_Ring_Pulse(P)) $\geq$ End(Enable_Ring(P)) + Uptime_Ring
& End(Disable_Ring_Pulse(P)) $\leq$ End(Enable_Ring(P)) + Uptime_Ring + Delta)

& FORALL P: Area_Phone
(Phone_State(P)=Ringing
& End(Disable_Ring_Pulse(P)) > Change(Phone_State(P))
& Now $\geq$ End(Disable_Ring_Pulse(P)) + Downtime_Ring + Delta
$\rightarrow$ End(Enable_Ring(P)) $\geq$ End(Disable_Ring_Pulse(P)) + Downtime_Ring
& End(Enable_Ring(P)) $\leq$ End(Disable_Ring_Pulse(P)) + Downtime_Ring+ Delta)

& FORALL P: Area_Phone
(~Long_Distance(P)
& Phone_State(P)=Waiting
& Now - End(Process_Local_Call(P)) $\geq$ Downtime_Ring
$\rightarrow$ EXISTS n,m:Integer
(End_n(Enable_Ring(Connected_To(P))) > End(Process_Local_Call(P))
& End_n(Enable_Ring(Connected_To(P))) $\leq$ End(Process_Local_Call(P)) + Downtime_Ring
& End_m(Enable_Ringback(P)) > End(Process_Local_Call(P))
& End_m(Enable_Ringback(P)) $\leq$ End_n(Enable_Ring(Connected_To(P))) + .5))

& FORALL P: Area_Phone
(Phone_State(P)=Waiting
& End(Enable_Ringback(P)) > Change(Phone_State(P))
& Now $\geq$ End(Enable_Ringback(P)) + Uptime_Ringback + Delta
$\rightarrow$ End(Disable_Ringback_Pulse(P)) $\geq$ End(Enable_Ringback(P)) + Uptime_Ringback
& End(Disable_Ringback_Pulse(P)) $\leq$ End(Enable_Ringback(P)) + Uptime_Ringback + Delta)

```
& FORALL P: Area_Phone
  (  Phone_State(P)=Waiting
  &  End(Disable_Ringback_Pulse(P)) > Change(Phone_State(P))
  &  Now ≥ End(Disable_Ringback_Pulse(P)) + Downtime_Ringback + Delta
  →     End(Enable_Ringback(P)) ≥ End(Disable_Ringback_Pulse(P)) +Downtime_Ringback
     &  End(Enable_Ringback(P)) ≤ End(Disable_Ringback_Pulse(P)) +Downtime_Ringback + Delta )


TRANSITION Give_Dial_Tone(P:Area_Phone) Tim1
ENTRY
     P.Offhook
  &  Phone_State(P) = Idle
EXIT
     Phone_State(P) BECOMES Ready_To_Dial
  &  Number(P) BECOMES NIL


TRANSITION Process_Digit(P:Area_Phone) Tim2
ENTRY
     P.Offhook
  &  ( (Long_Distance(P) & Count(P) < 11)
     | (~Long_Distance(P) & Count(P) < 7))
  &  (   (  Phone_State(P)=Ready_To_Dial
         &  P.End(Enter_Digit) > End(Give_Dial_Tone(P)))
     |   (  Phone_State(P)=Dialing
         &  P.End(Enter_Digit) > End(Process_Digit(P))))
EXIT
     IF Count'(P) = 0
     THEN
         IF P.Next_Digit' = 1
         THEN Long_Distance(P) BECOMES True
         ELSE Long_Distance(P) BECOMES False
         FI
         & Phone_State(P) BECOMES Dialing
     FI
  & Number(P) BECOMES
         Number'(P) CONCAT LISTDEF(P.Next_Digit')


TRANSITION Process_Local_Call(P:Area_Phone)     Tim3
ENTRY
     P.Offhook
  &  ~Long_Distance(P)
  &  Count(P)=7
  &  Phone_State(P)=Dialing
  &  ~Get_ID(Number(P)).Offhook
  &  Phone_State(Get_ID(Number(P)))=Idle
EXIT
     Phone_State(Get_ID(Number'(P))) = Ringing
  &  Phone_State(P) = Waiting
  &  ~Long_Distance(Get_ID(Number'(P)))
  &  Connected_To(P) = Get_ID(Number'(P))
  &  Connected_To(Get_ID(Number'(P))) = P
  &  FORALL P1:Area_Phone
     (   P1≠P & P1≠Get_ID(Number'(P))
     →   NOCHANGE(Phone_State(P1))
     &   NOCHANGE(Connected_To(P1)))
```

```
EXCEPT
        P.Offhook
    &   ~Long_Distance(P)
    &   Count(P)=7
    &   Phone_State(P)=Dialing
    &   (   Get_ID(Number(P)).Offhook
        |   Phone_State(Get_ID(Number(P)))≠Idle)
EXIT
        Phone_State(P) BECOMES Busy


TRANSITION Connect_Long_Distance(P:Area_Phone) Tim4
ENTRY
        P.Offhook
    &   Count(P) = 11
    &   Long_Distance(P)
    &   Phone_State(P) = Dialing
    &   Pick_Area(Number(P)) ≠ Get_Area(Self)
EXIT
        LDOut_Line(P)[From_Area] = Get_Area(Self)
    &   LDOut_Line(P)[From_Number]= Get_Number(P)
    &   LDOut_Line(P)[To_Area]= Pick_Area(Number'(P))
    &   LDOut_Line(P)[To_Number]=Pick_Number(Number'(P))
    &   LDOut_Status(P) BECOMES In_Progress
    &   Phone_State(P) BECOMES Calling
    &   FORALL P1: Area_Phone
            (P1 ≠ P → NOCHANGE(LDOut_Line(P1)))
EXCEPT
        P.Offhook
    &   Count(P) = 11
    &   Long_Distance(P)
    &   Phone_State(P) = Dialing
    &   Pick_Area(Number(P)) = Get_Area(Self)
EXIT
        Long_Distance(P) BECOMES False
    &   Number(P) BECOMES Pick_Number(Number'(P))


TRANSITION Enable_Ring(P:Area_Phone) Tim5
ENTRY
        ~P.Offhook
    &   Phone_State(P)=Ringing
    &   ~Enabled_Ring_Pulse(P)
    &   FORALL t: Time
        (   End(Disable_Ring_Pulse(P), t)
        &   FORALL t1 : Time
            (t ≤ t1 ≤ Now → past(Phone_State(P),t1)=Ringing)
        →   Now - t ≥ Downtime_Ring)
EXIT
        Enabled_Ring_Pulse(P) BECOMES True


TRANSITION Disable_Ring_Pulse(P:Area_Phone)    Tim6
ENTRY
        Enabled_Ring_Pulse(P)
    &   (   Now - End(Enable_Ring(P))≥ Uptime_Ring
        |   P.Offhook)
EXIT
        Enabled_Ring_Pulse(P) BECOMES False
```

```
TRANSITION Enable_Ringback(P:Area_Phone) Tim7
ENTRY
        P.Offhook
    &   Phone_State(P)=Waiting
    &   ~Enabled_Ringback_Pulse(P)
    &   FORALL t: Time
        (   End(Disable_Ringback_Pulse(P), t)
        &   FORALL t1 : Time
            (t ≤ t1 ≤ Now → past(Phone_State(P),t1)=Ringing)
        →   Now - t ≥ Downtime_Ringback)
EXIT
        Enabled_Ringback_Pulse(P) BECOMES True

TRANSITION Disable_Ringback_Pulse(P:Area_Phone) Tim8
ENTRY
        Enabled_Ringback_Pulse(P)
    &   ( Now - End(Enable_Ringback(P)) ≥ Uptime_Ringback
        | ~P.Offhook)
EXIT
        Enabled_Ringback_Pulse(P) BECOMES False

TRANSITION Receive_LD (LDIn_Line:Connection) Tim9
ENTRY
        LDIn_Line[To_Area] = Get_Area(Self)
    &   Phone_State(Get_ID(LDIn_Line[To_Number])) = Idle
    &   ~Get_ID(LDIn_Line[To_Number]).Offhook
EXIT
        Phone_State(Get_ID(LDIn_Line[To_Number]))
                                        BECOMES Ringing
    &   LDOut_Status(Get_ID(LDIn_Line[To_Number]))
                                        BECOMES Connected
    &   Plug(   LDOut_Line(Get_ID(LDIn_Line[To_Number])),
                LDIn_Line)
    &   FORALL P: Area_Phone
        (   P ≠ Get_ID(LDIn_Line[To_Number])
        →   NOCHANGE(LDOut_Line(P)))

TRANSITION Start_Talk_1(P:Area_Phone) Tim10
ENTRY
        P.Offhook
    &   Phone_State(P)=Ringing
EXIT
        Phone_State(P)=Talk
    &   IF ~Long_Distance(P)
        THEN
            Phone_State(Connected_To'(P))=Talk
        &   FORALL P1:Area_Phone
            (   P1≠P & P1≠Connected_To'(P)
            →   NOCHANGE(Phone_State(i)))
        ELSE LDOut_Status(P) BECOMES Talking
        FI

TRANSITION Start_Talk_2(LDIn_Line:Connection) Tim11
ENTRY
        EXISTS P: Area_Phone
        (   Calling_Out(P,LDIn_Line)
        &   Phone_State(P) = Waiting
        &   LDOut_Status(P) = Connected)
```

```
EXIT
        EXISTS P: Area_Phone
        (   Calling_Out'(P,LDIn_Line)
        &   Phone_State'(P) = Waiting
        &   LDOut_Status'(P) = Connected
        &   LDOut_Status(P) BECOMES Talking
        &   Phone_State(P) BECOMES Talk)

TRANSITION Start_LD(LDIn_Line:Connection,LDIn_Status: Connection_Status) Tim12
ENTRY
        LDIn_Status = Connected
    &   EXISTS P: Area_Phone
        (   Calling(P,LDIn_Line)
        &   Phone_State(P) = Calling
        &   LDOut_Status(P) = In_Progress)
EXIT
        EXISTS P: Area_Phone
        (   Calling'(P,LDIn_Line)
        &   Phone_State'(P) = Calling
        &   LDOut_Status'(P) = In_Progress
        &   LDOut_Status(P) BECOMES Connected
        &   Phone_State(P) BECOMES Waiting)
EXCEPT
        LDIn_Status = Disconnected
    &   EXISTS P: Area_Phone
        (   Calling(P,LDIn_Line)
        &   Phone_State(P) = Calling
        &   LDOut_Status(P) = In_Progress)
EXIT
        EXISTS P: Area_Phone
        (   Calling'(P,LDIn_Line)
        &   Phone_State'(P) = Calling
        &   LDOut_Status'(P) = In_Progress
        &   LDOut_Status(P) BECOMES Available
        &   Phone_State(P) BECOMES Busy)

TRANSITION Terminate_LD_1(P:Area_Phone) Tim13
ENTRY
        ~P.Offhook
    &   Long_Distance(P)
    &   Phone_State(P) ≠ Idle & Phone_State(P) ≠ Ringing
    &   LDOut_Line(P)[From_Area] = Get_Area(Self)
    &   LDOut_Line(P)[From_Number] = Get_Number(P)
    &   LDOut_Status(P) ≠ Available
EXIT
        Phone_State(P) BECOMES Idle
    &   LDOut_Status(P) BECOMES Available

TRANSITION Generate_Alarm(P:Area_Phone) Tim14
ENTRY
        P.Offhook
    &   (   Phone_State(P)=Ready_To_Dial
        |   (   Phone_State(P)=Dialing
            &   P.Call(Enter_Digit) < Start(Process_Digit(P))))
    &   (   Count(P)=0 & (Now-End(Give_Dial_Tone(P))) > 30
        |   (   Count(P)>0
            &   (   ~Long_Distance(P) & Count(P)<7
                |   Long_Distance(P) & Count(P)<11)
            &   (   (Now - End(Process_Digit(P))) > 20
                |   (Now - End(Give_Dial_Tone(P))) > 100 ))
```

```
EXIT
        Phone_State(P) BECOMES Alarm

TRANSITION Terminate_Local_Call(P:Area_Phone) Tim15
ENTRY
        ~P.Offhook
    &   ~Long_Distance(P)
    &   Phone_State(P)≠Idle & Phone_State(P)≠ Ringing
EXIT
        Phone_State(P)=Idle
    &   IF Phone_State'(P)=Talk | Phone_State'(P)=Waiting
        THEN
            IF Phone_State'(P)=Talk
            THEN Phone_State(Connected_To'(P))=Disconnect
            ELSE Phone_State(Connected_To'(P))=Idle
            FI
        &   FORALL P1:Area_Phone
            (   P1≠P & P1≠Connected_To'(P)
            →  NOCHANGE(Phone_State(P1)))
        ELSE
            FORALL P1:Area_Phone
            (   P1≠P→ NOCHANGE(Phone_State(P1)))
        FI

TRANSITION Terminate_LD_2(LDIn_Line:Connection) Tim16
ENTRY
        EXISTS P: Area_Phone
        (   Calling_Out(P,LDIn_Line)
        &   Phone_State(P) = Talk
        &   LDOut_Status(P) = Talking)
EXIT
        EXISTS P: Area_Phone
        (   Calling_Out'(P,LDIn_Line)
        &   Phone_State'(P) = Talk
        &   LDOut_Status'(P) = Talking
        &   LDOut_Status(P) BECOMES Disconnected
        &   Phone_State(P) BECOMES Disconnect)
EXCEPT
        EXISTS P: Area_Phone
        (   Calling_Out(P,LDIn_Line)
        &   Phone_State(P) = Ringing
        &   LDOut_Status(P) = Connected)
EXIT
        EXISTS P: Area_Phone
        (   Calling_Out'(P,LDIn_Line)
        &   Phone_State'(P) = Ringing
        &   LDOut_Status'(P) = Connected
        &   LDOut_Status(P) BECOMES Available
        &   Phone_State(P) BECOMES Idle)


FURTHER ASSUMPTIONS
    CONSTANT REFINEMENT
        2 > MAX(Tim1, …, Tim16) + Max_Cust*Tim1
    TRANSITION SELECTION
        {Give_Dial_Tone, *} TRUE → {Give_Dial_Tone}


END Top_Level
END Central_Control
```

Appendix B The Long Distance Network

```
GLOBAL SPECIFICATION Long_Distance_Network

PROCESSES
    Units: array[1 .. Num_Area] of Long_Distance_Unit

TYPE
    Digit IS TYPEDEF d: Integer (d ≥ 0 & d ≤ 9),
    Positive_Integer IS TYPEDEF p: Integer (p > 0),
    Line,
    LDU_ID IS TYPEDEF pid: ID (IDTYPE(pid) = Long_Distance_Unit),
    Digit_List IS LIST OF Digit,
    Connection_Status = (Available, In_Progress, Disconnected, Connected, Talk),
    Connection IS STRUCTURE OF (From_Area, From_Number, To_Area, To_Number: Digit_List)

CONSTANT
    Num_Area: Positive_Integer

DEFINE
    Connect(L1, L2: Connection): Boolean ==
            L1[From_Area] = L2[From_Area]
        &   L1[From_Number] = L2[From_Number]
        &   L1[To_Area] = L2[To_Area]
        &   L1[To_Number] = L2[To_Number],

    Disconnect(L: Connection): Boolean ==
            L[From_Area] = NIL
        &   L[To_Area] = NIL
        &   L[From_Number] = NIL
        &   L[To_Number] = NIL,

    Plug(L1, L2: Connection): Boolean ==
            L1[From_Area] = L2[To_Area]
        &   L1[From_Number] = L2[To_Number]
        &   L1[To_Area] = L2[From_Area]
        &   L1[To_Number] = L2[From_Number]

END Long_Distance_Network


SPECIFICATION Long_Distance_Unit
LEVEL Top_Level

IMPORT
    Digit, Digit_List, Line, LDU_ID, Connection_Status, Connection, Plug, Connect, Disconnect

EXPORT
    NetOut, LocOut, NetStatus, LocStatus, Receive_Local_Req, Local_Established, Started_Local_Talk, End_Local

VARIABLE
    NetOut(Line), LocOut(Line): Connection,
    NetStatus(Line), LocStatus(Line): Connection_Status

CONSTANT
    Ti1, Ti2, Ti3, Ti4, Ti5, Ti6, Ti7, Ti8, Ti9, Timeout, Max_Calls: Time,
    Get_Area(LDU_ID): Digit_List

ENVIRONMENT
    FORALL t: Time, L: Connection
    (   Call(End_Local(L), t) → EXISTS L1: Line (Connect(past(NetOut(L1), t), L) & past(NetStatus(L1), t) ≠ Available)
    &   Call(Local_Established(L),t) → EXISTS L1:Line (Plug(past(LocOut(L1),t),L) & past(NetStatus(L1),t) ≠ Connected)
    &   Call(Started_Local_Talk(L),t)→ EXISTS L1:Line (Plug(past(LocOut(L1),t),L) & past(NetStatus(L1),t)=Connected))
&   FORALL t:Time (Call2(Receive_Local_Req, t) → Call(Receive_Local_Req) - Call2(Receive_Local_Req) > Max_Calls)
```

```
INITIAL
    FORALL L: Line
    (Disconnect(NetOut(L)) & Disconnect(LocOut(L)) & NetStatus(L) = Available & LocStatus(L) = Available)


TRANSITION Receive_Local_Req (In_Line: Connection) Ti1
ENTRY
    In_Line[From_Area] = Get_Area(Self)
EXIT
    EXISTS L: Line
    (   NetStatus'(L) = Available
    &   Connect(NetOut(L), In_Line)
    &   NetStatus(L) BECOMES In_Progress
    &   FORALL L1:Line(L1≠L→NOCHANGE(NetOut(L1))))


TRANSITION Receive_Long_Req Ti2
ENTRY
    EXISTS U: LDU_ID, L: Line
    (   U.NetOut(L)[To_Area] = Get_Area(Self)
    &   U.NetStatus(L) = In_Progress
    & FORALL L1:Line(~Connect(U.NetOut(L),LocOut(L1))))
EXIT
    EXISTS U: LDU_ID, L: Line
    (   U.NetOut'(L)[To_Area] = Get_Area(Self)
    &   U.NetStatus'(L) = In_Progress
    &   FORALL L1:Line(~Connect(U.NetOut'(L),LocOut'(L1))
        &   Connect(LocOut(L), U.NetOut'(L))
        &   LocStatus(L) BECOMES In_Progress)
    &   FORALL L1:Line(L1≠L→NOCHANGE(LocOut(L1))))


TRANSITION Local_Established (In_Line: Connection) Ti3
ENTRY
    In_Line[From_Area] = Get_Area(Self)
&   EXISTS L: Line
    (Plug(LocOut(L), In_Line)&NetStatus(L)≠Connected)
EXIT
    EXISTS L: Line
    (   Plug(LocOut'(L), In_Line)
    &   NetStatus'(L) ≠ Connected
    &   NetStatus(L) BECOMES Connected
    &   Connect(NetOut(L), In_Line)
    &   FORALL L1:Line(L1≠L→NOCHANGE(NetOut(L1))))


TRANSITION Long_Established Ti4
ENTRY
    EXISTS U: LDU_ID, L: Line
    (   U.NetOut(L)[To_Area] = Get_Area(Self)
    &   U.NetStatus(L)=Connected & LocStatus(L)≠Connected)
EXIT
    EXISTS U: LDU_ID, L: Line
    (   U.NetOut'(L)[To_Area] = Get_Area(Self)
    &   U.NetStatus'(L) = Connected
    &   LocStatus'(L) ≠ Connected
    &   LocStatus(L) BECOMES Connected
    &   Connect(LocOut(L), U.NetOut'(L))
    &   FORALL L1:Line(L1≠L→NOCHANGE(LocOut(L1))))
```

```
TRANSITION Started_Local_Talk (In_Line: Connection) Ti6
ENTRY
    EXISTS L: Line
    (Plug(LocOut(L),In_Line) & NetStatus(L)=Connected)
EXIT
    EXISTS L: Line
    (   Plug(LocOut'(L), In_Line')
    &   NetStatus'(L) = Connected
    &   NetStatus(L) BECOMES Talk)


TRANSITION Send_Local_Timeout Ti5
ENTRY
    EXISTS L: Line
    (   NetStatus(L) = In_Progress
    &   LocStatus(L) = Available
    &   Now-End(Receive_Loc_Req(NetOut(L)))≥Timeout)
EXIT
    EXISTS L: Line
    (   NetStatus'(L) = In_Progress
    & Now-End(Receive_Local_Req(NetOut'(L)))≥Timeout+Ti5
    &   LocStatus(L) BECOMES Disconnected
    &   NetStatus(L) BECOMES Available)


TRANSITION Started_Long_Talk Ti7
ENTRY
    EXISTS U: LDU_ID, L: Line
    (   Connect(U.NetOut(L), LocOut(L))
    &   U.NetStatus(L) = Talk
    &   LocStatus(L) = Connected)
EXIT
    EXISTS U: LDU_ID, L: Line
    (   Connect(U.NetOut'(L), LocOut'(L))
    &   U.NetStatus'(L) = Talk
    &   LocStatus(L) BECOMES Talk)


TRANSITION End_Local (In_Line: Connection) Ti8
ENTRY
    EXISTS L: Line (Connect(NetOut(L), In_Line))
EXIT
    EXISTS L: Line
    (   Connect(NetOut'(L), In_Line')
    &   Disconnect(NetOut(L))
    &   Disconnect(LocOut(L))
    &   NetStatus(L) BECOMES Available
    &   LocStatus(L) BECOMES Available
    &   FORALL L1:Line
        (   L1 ≠ L
        →   NOCHANGE(LocOut(L1))
        &   NOCHANGE(NetOut(L1))))
```

```
TRANSITION End_Long Ti9
ENTRY
    EXISTS L: Line
    (   ~Disconnect(LocOut(L))
    &  LocStatus(L) ≠ Available
    &  FORALL U: LDU_ID, L1: Line
        (    ~Connect(U.NetOut(L1), LocOut(L))))
EXIT
    EXISTS L: Line
    (   ~Disconnect(LocOut'(L))
    & LocStatus'(L) ≠ Available
    &  FORALL U: LDU_ID, L1: Line
        (    ~Connect(U.NetOut'(L1), LocOut'(L)))
    &  Disconnect(LocOut(L))& Disconnect(NetOut(L))
    &  LocStatus(L) BECOMES Available
    &  NetStatus(L) BECOMES Available
    &  FORALL L1: Line
        (    L1 ≠ L
        →  NOCHANGE(LocOut(L1))
        &  NOCHANGE(NetOut(L1))))


END Top_Level
END Long_Distance_Unit
```

Appendix C The Compose Section

```
COMPOSITION OF Phone_System, Long_Distance_Network AS Phone_Network

PROCESSES
    Phones: array[1 .. Num_Phone] of Phone,
    Centrals: array[1 .. Num_Area] of Central_Control
    Units: array[1 .. Num_Area] of Long_Distance_Unit

CONSTANT
    LD_Unit(Central_Control_ID): LDU_ID

AXIOM
    FORALL C1, C2: Central_Control_ID (LD_Unit(C1) = LD_Unit(C2) → C1 = C2)


TRIGGERS
    CALL GENERATION FOR Long_Distance_Unit.Receive_Local_Req
        FORALL t: Time, P: Phone_ID
        (    Change(In_Area(P).LDOut_Status(P),t) & In_Area(P).LDOut_Status(P) = In_Progress
        ↔  LD_Unit(In_Area(P)).Call(Receive_Local_Req(In_Area(P).LDOut_Line(P)), t))

    CALL GENERATION FOR Long_Distance_Unit.Local_Established
        FORALL t: Time, P: Phone_ID
        (    Change(In_Area(P).LDOut_Status(P),t) & In_Area(P).LDOut_Status(P) = Connected
        &   Change(In_Area(P).Phone_State(P),t) & In_Area(P).Phone_State(P) = Ringing
        ↔  LD_Unit(In_Area(P)).Call(Local_Established(In_Area(P).LDOut_Line(P)), t))

    CALL GENERATION FOR Long_Distance_Unit.Started_Local_Talk
        FORALL t: Time, P: Phone_ID
        (    Change(In_Area(P).LDOut_Status(P),t) & In_Area(P).LDOut_Status(P) = Talk
        &   EXISTS t1: Time
            (    FORALL t2 : Time (t2 ≥ t1 & t2 < t → ~past(Change(In_Area(P).LDOut_Status(P),t2),t2))
            &   past(In_Area(P).LDOut_Status(P),t1) = Connected & past(In_Area(P).Phone_State(P),t1) = Ringing)
        ↔  LD_Unit(In_Area(P)).Call(Started_Local_Talk(In_Area(P).LDOut_Line(P)), t))

    CALL GENERATION FOR Long_Distance_Unit.End_Local
        FORALL t: Time, P: Phone_ID
        (    Change(In_Area(P).LDOut_Status(P),t) & In_Area(P).LDOut_Status(P) = Available
        ↔  LD_Unit(In_Area(P)).Call(End_Local(In_Area(P).LDOut_Line(P)), t))

    CALL GENERATION FOR Central_Control.Receive_LD
        FORALL t: Time, C: Central_Control_ID, L: Line
        (    LastChg(LD_Unit(C).LocStatus(L),t) & LD_Unit(C).LocStatus(L) = In_Progress
        ↔  C.Call(Receive_LD(LD_Unit(C).LocOut(L)), t))

    CALL GENERATION FOR Central_Control.Start_LD
        FORALL t: Time, C: Central_Control_ID, L: Line
        ( Change(LD_Unit(C).LocStatus(L),t) & past(LD_Unit(C).LocStatus(L),t)=Connected
        & ~Change(LD_Unit(C).NetOut(L),t)
        & (LD_Unit(C).NetStatus(L) = Connected | LD_Unit(C).NetStatus(L) = Available)
        ↔  C.Call(Start_LD(LD_Unit(C).LocOut(L), LD_Unit(C).LocStatus(L)), t))

    CALL GENERATION FOR Central_Control.Terminate_LD_2
        FORALL t: Time, L: Line, P: Phone_ID
        (    Change(LD_Unit(In_Area(P)).LocOut(L),t) & past(LD_Unit(In_Area(P)).LocStatus(L), t) = Available
        &   Change(LD_Unit(In_Area(P)).NetOut(L),t) & past(LD_Unit(In_Area(P)).NetStatus(L), t) = Available
        &   (past(In_Area(P).LDOut_Status(P), t) = Talk | past(In_Area(P).LDOut_Status(P), t) = Connected)
        ↔  In_Area(P).Call(Terminate_LD_Call_2(LD_Unit(In_Area(P)).LocOut(L)), t))


END COMPOSITION
```