TEMPORAL REASONING IN A COGNITIVE RADIO SYSTEM

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Abstract

Understanding and reasoning over time is a critical enabling technology for intelligent machine behavior. Actions, states, and observed events can be modeled within the context of temporal events and their relationships. This enables the construction of temporal patterns that may be used by cognitive radio systems to proactively adapt and reconfigure themselves based on situational state. By providing a common temporal reference system, experiential knowledge can be shared between radio systems through the abstraction and propagating temporal patterns. Temporal reasoning can also be used to extend the robustness of radio environment maps. This paper explores qualitative and quantitative temporal reasoning within a radio system. A key aspect is a compact representation and efficient computation of transitive relationships within a digital processor.

1. Introduction

The ability to reason over time is a fundamental capability of intelligent systems. The basic assertion proposed in this paper that reasoning over time enables a cognitive radio system to more effectively function within its environment.

There are multiple perspectives of time within a radio system. Signal processing elements of the radio system require accurate, high-resolution time in order to maintain processing synchronization. For example, the spurious clock jitter to an Analog-to-Digital Converter (ADC) can result in sample errors that are interpreted as phase changes in the waveform signal.

This discrete perspective of time, while critical for signal processing, is less useful for cognitive radio functions that address intelligent operations within the context of a mission scenario. In this case, the ability to understand and reason over time in the context of events, their duration, and relationships between the temporal intervals that represent the extent of the underlying events. For example, in the context of dynamic spectrum access, the ability of a radio to reason over temporal patterns of spectrum availability would enable a cognitive radio to perform predictive dynamic spectrum access.

1.1. Temporal Representation

Multiple approaches to temporal representation and reasoning have been proposed ranging from systems based on time points, to constraint-based directed graph representation, to temporal intervals. The approach presented in this paper is based on the temporal interval approach proposed by Allen [1] and refined by the author [2].

1.2. Temporal Intervals

The basic concept of an interval-based temporal system is that, instead of discrete time points, the essential aspect of temporal reasoning is the ability to understand the relationships between events or actions. These events or actions occur over some temporal extent, an interval, and can be ordered based on the temporal relationships.

A simple example is the statement, "After stopping for gas, I went to pick up paint and then met my wife for lunch." There is no specific time value or reference point specified in the statement, yet most individuals have absolutely no difficulty building and understanding a temporal model of the relationships and order of the events referenced in the statement.

This ability to understand and reason over time in a *qualitative* fashion is critical for cognitive radio systems. It enables a radio system to represent and reason over event and sensor data relationships and patterns without being bound by the limitations of requiring explicit time values.

2. Temporal Relationships

In Allen's work on interval-based temporal reasoning, the basic tenet was the assignment of a relationship between two temporal intervals. The base relationships are illustrated in figure 1. These relationships, together with their inverses result in thirteen possible relationships. Note that the inverse of equals is itself. So, there are six inverse relationships in addition to those shown in the figure for a total of thirteen.

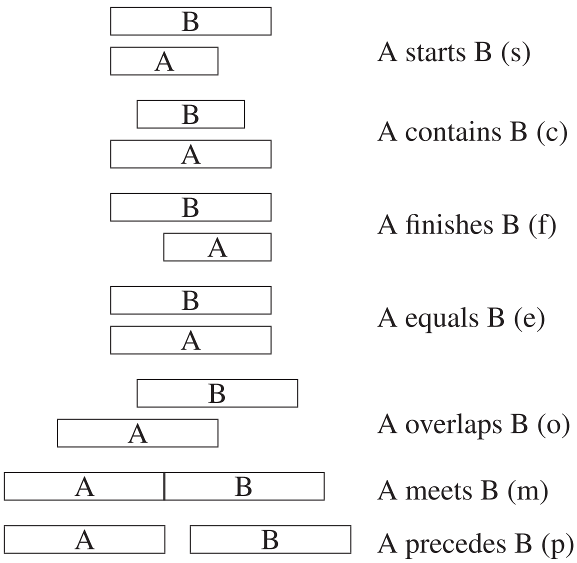

Figure 1. Allen's Temporal Interval Relations

These relationships and their inverse form thirteen temporal relations that may be asserted between two temporal intervals. For example, the inverse of *overlaps* is *overlapped-by*. So, if A *overlaps* B, the inverse relationship is B *overlapped-by* A.

The relations will be abbreviated using the first letter of the relationship, e.g. *overlaps* will be represented as o, etc. The inverse relationship is represented as the relation raised to the power of negative one. Thus the inverse of o is o^{-1}.

Using the above relationships, we can represent the relationships between the temporal events expressed in the example sentence above. The sentence can be broken down into the following temporal events:

A: Get gas

B: Pick up paint

C: Meet wife

D: Have lunch

E: Wife arrives

It should be noted that events D and E were not explicitly stated in the sentence. It was simply said that I met my wife for lunch. However, the implicit assumptions are that my wife traveled and arrived at the same location for lunch and then we ate lunch together.

Thus the temporal relationships for the above sentence are:

- A *precedes* B
- B *precedes* C
- C *finishes — finished-by* E
- C *meets* D

The above example illustrates a couple of interesting aspects of interval-based temporal reasoning. First, in 'C *finishes — finished-by* E' the possibly is expressed that either I or my wife may have arrived first but when *both* of us had completed the *arrive* event, we then had lunch. Certainly one could make the case that an alternative temporal relationship would be to decomposed the arrive event into arriving and waiting. However, for this simple example, the waiting performed by whoever arrived first is part of the arrival.

The second interesting aspect is that there inferred actions, e.g. E, and relationships, e.g. A *precedes* C. The relationship inference is of particular interest in this paper because it illustrates the computation of transitive relationships between two intervals, A and C, through relationships each has with a common interval, B.

The following subsection discusses the interval concepts further and provides the foundation for the representation and reasoning approach as applied to a cognitive radio system

2.1. Interval Properties

Let i represent a temporal interval with some duration, d, that represents the temporal extent or time over which the event represented by the interval occurs or exists. The fundamental premise of Allen's temporal algebra is that the basic unit is interval time rather than point time. However, the duration of an interval may be arbitrarily small. Thus, as $d \to 0$, i takes on the characteristics of a point. This aspect of temporal intervals is dependent on the time scale used within the temporal system. For example, a single clock cycle on a high-speed Central Processing Unit (CPU) has no meaningful frame of reference for the computer user and may be viewed as a point. However, within the digital electronics of the processor, the clock cycle time is a significant, non-zero duration of time.

A temporal interval, i, is defined as having a start, i_s, and end, i_e. An underlying assumption is that time progresses in a single directions such that $i_s \leq i_e$ holds for all values of s and e.

The temporal distance or duration, d, of the interval is the temporal difference between the start and end of the interval, $i_d = i_e - i_s$. Since the start of an interval is always less than or equal to the end of the interval, the temporal extent or duration of an interval is always greater than or equal to zero, $i_d \geq 0$.

However, the preceding assertion implies that the duration can be zero. Thus, as the start and end of an interval approach each other, the duration of the interval approaches zero and the interval takes on the characteristics of a temporal point. So, an interval can exhibit the properties of a time point, p. This enables the ability to represent both points and intervals within the same representation framework.

2.2. Interval Point Relationships

It has already been asserted that the start of an interval, i_s is less than or equal to the end of the interval, i_e. Since an interval takes on the characteristics of a point as it's duration approaches zero, the relationships that may exist between two points is *less than* $<$, *greater than* $>$, *equal to* $=$, or *unknown* $\lesseqgtr$. Combining this concept with Allen's temporal interval relationships allows us to define the set of temporal relationships in terms of relationships between the start and end of the interval pair. For example, the relationship, A *overlaps* B, can be represented by relationships between each of the endpoints. This is illustrated in table 1.

Table 1. Start and End Relationships for A *overlaps* B

A End Points	B End Points	Relation
A_s	B_s	$<$
A_s	B_e	$<$
A_e	B_s	$>$
A_e	B_e	$<$

However, endpoint relationships noted above does not facilitate the representation and computation of temporal relations by digital means. Thus, a binary signature is assigned to each possible endpoint relationship. The binary assignments are shown in Table 2.

Table 2. Encoding of Endpoint Relationships

Name	Symbol	Code
equal	$=$	00
less	$<$	01
greater	$>$	10
unknown	$\lesseqgtr$	11

Substituting these codes for the relationship symbols shown in table 1 yields table 3

Table 3. Binary endpoint relationships for A *overlaps* B

End Point Relationships		
A	B	Code
A_s	B_s	01
A_s	B_e	01
A_e	B_s	10
A_e	B_e	01

This table of binary relations can be reformatted into a 2-by-2 matrix and represented as shown in table 4.

Table 4. Binary matrix for A *overlaps* B

AB	B_s	B_e
A_s	01	01
A_e	10	01

This approach exhibits multiple benefits. First, a range of potential temporal relationships can be represented in a single, 8-bit word. Second, an algorithm was developed that computes the transitive relationship between a set of three intervals that utilizes basic digital logic. Third, an algorithm that computes the transitive closure over a set of temporal relations was developed that, on the average, runs in $n\log(n)$ time rather than polynomial time.

2.3. Efficient Representation

As can be seen by this encoding, taking the binary values in row-column order the temporal relationship can be represented as the 8-bit value, 01011001. As described in [3], this provides a compact representation for a qualitative relationship between two interval without requiring explicit values for the start and end of either relation.

While the representation of temporal events as intervals provides a natural mechanism for reasoning over time in a qualitative fashion, the complexity of computing the transitive closure over the full set of thirteen relationships presents an intractable problem. This is further exacerbated by the fact that radio system typically do not have significant general purpose processing resources to devote to complex temporal reasoning.

2.4. Transitive Computation

As noted previously, a core capability for a temporal system is the computation of transitive relationships. Computing the transitive relationship can, however, result in ambiguity. For example, if it is asserted that A *overlaps* B, and B *overlaps* C, Allen's temporal algebra states that the relationship between A and C must be in the set p, m, o, precedes, meets, or overlaps. This is illustrated in figure 2.

However, ambiguities may arise during the computation of transitive relationships. Consider the three interval A, B, and C, for example. If A overlaps B and B overlaps C, computing the transitive relationship between A and C yields ambiguities, i.e. A may precede, meet, or overlap C. Thus the end-point relationship between the end of A and the start of B may be $<$, $=$, or $>$. This ambiguity is represented by the symbol $\lesseqgtr$.

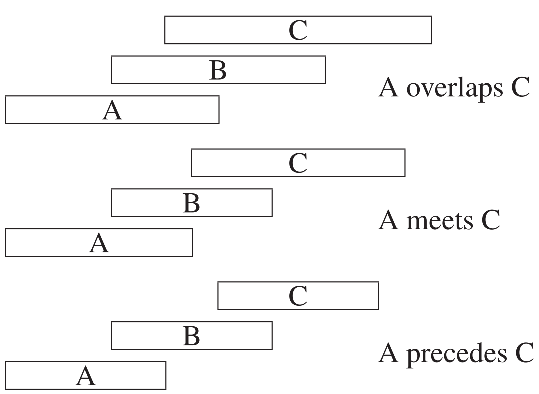

Figure 2. Transitive relationships between A and C for A *precedes* B and B *overlaps* C

Thus the only end-point relationship pair that is ambiguous is (A_e, C_s). Thus the transitive relationship computation, $\otimes$, of (A, B) and (B, C) must yield an unknown relationship, $\lesseqgtr$, between A_e and C_s. Figure 3 illustrates this computation.

AB	B_s	B_e
A_s	01	01
A_e	10	01

$\otimes$

BC	C_s	C_e
B_s	01	01
B_e	10	01

$\Rightarrow$

AC	C_s	C_e
A_s	01	01
A_e	11	01

Figure 3. Computing transitive closure for A and C

The algorithm to compute the transitive relationship, $A \otimes C$ is a variant of the standard matrix multiplication algorithm. The common matrix multiplication algorithm is expressed by equation 1.

$$(AB)_{ij} = \sum_{r=1}^{n} a_{ir} b_{rj} = a_{i1} b_{1j} + a_{i2} b_{2j} + \ldots + a_{in} b_{nj} \quad (1)$$

Because of the binary representation, the 'sum of products' matrix multiplication algorithm operations are changed to the boolean OR operator for the product and the boolean AND operator for the sum. This is shown in equation 2.

$$(A \otimes B)_{ij} = \sum_{r=1}^{n} a_{ir} b_{rj} = a_{i1} \vee b_{1j} \wedge a_{i2} \vee b_{2j} \wedge \ldots \wedge a_{in} \vee b_{nj} \quad (2)$$

However, since the temporal matrix is a simple square matrix of four elements, the general transitive computation algorithm is reduced to the form shown in equation 3.

$$(A \otimes B)_{ij} = \sum_{r=1}^{2} a_{ir} b_{rj} = a_{i1} \vee b_{1j} \wedge a_{i2} \vee b_{2j} \quad (3)$$

While standard matrix multiplication algorithms are computed sequentially using an iterative loop, because of the binary representation and the fact that the temporal matrix consists of four, two-bit elements, a Temporal Logic Unit (TLU) can be assembled to implement the transitive computation as a simple combinatorial logic circuit.

2.5. Computing Transitive Closure

A key capability for a temporal representation and reasoning capability is the ability to compute the transitive closure over the set of temporal relationships as new relationships are asserted, intervals are added, or removed.

In order to be useful, the computation of the transitive closure must be performed in an efficient manner, Therefore an algorithm for computing the transitive closure that utilizes the binary representation will provide a more efficient approach due to the fact that it can be easily implemented using digital hardware.

Discussion of the transitive closure algorithm is outside the scope of this paper. The reader is referred to [2] for a discussion and an example implementation of the algorithm. However, the key element is that the algorithm provides a method for maintaining consistency and, more importantly, removing ambiguity, as new intervals are added and relationships are asserted and retracted. This capability is critical to maintaining a comprehensive temporal system within the cognitive radio while supporting potential ambiguities between temporal interval endpoints.

3. Radio System Temporal Reasoning

As previously noted, an integrated temporal reasoning system enables the radio system to do more than simply react to existing environmental conditions. It enables the radio system to remember historical conditions and, based on the memories of those conditions of their temporal order, anticipate and adapt to expected patterns of spectrum availability, interference, and visibility *before* they occur.

3.1. Temporal Spectrum Planning

Temporal Spectrum Planning can be viewed as a set of spectrum temporal intervals organized by time and frequency. Illustrated in figure 4, each interval represents an instance of spectrum usage organized by frequency and time.

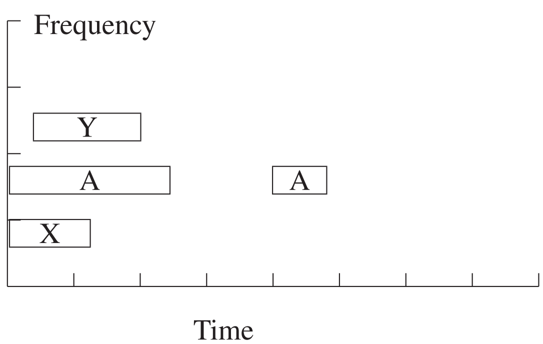

Figure 4. Temporal Spectrum Planning

Another way of interpreting the temporal spectrum map is as the presence of data content by frequency over time in a Frequency Division Multiplexing (FDM) modulated waveform. A key capability is that the temporal spectrum interval map is time frame agnostic. That is, the key aspect if the relationship between the temporal spectrum intervals. These intervals may consist of a mix of past events, current observations, and future activities or anticipated events, all within a single coherent representation.

3.2. Temporal Pattern Recognition

While the use of temporal intervals can be applied to spectrum planning, they can also be used in an observational mode to develop recognizable patterns of spectrum usage. As periodic measurements of spectrum are made during operation normal operations, a temporal spectrum map is developed. Similar to the temporal map illustrated in figure 4 in content, the pattern recognition map is constructed based on empirical observations of spectrum occupancy. The observed spectrum usage provides baseline input to a temporal structure analysis element that abstracts discrete times of spectral activity into general patterns of frequency usage.

Each temporal pattern consists of a set of event types, e.g. occupied spectrum in a given frequency range. Thus, a temporal pattern can be represented as the pattern of relationship values ordered by event type. This dimension facilitates the recognition of event patterns by comparison of the relationship bit vectors between the sequence of events observed and the pattern of interval event types stored within the radio's memory.

Once a temporal pattern of spectrum usage is generated, it can then be used as a set of input constraints to the temporal planning component. Functioning as a cooperative pair, the cognitive radio system embodies basic spectrum planning based on observations with the ability to improve or learn pattern changes as they evolve.

4. Temporal Extensions

Once the basic temporal representation and reasoning engine is embodied within a radio system, there are several capabilities that are natural extension. These include:

- autonomous learning,
- identifying exceptional events based on expectations, and
- providing bootstrap knowledge for other radio systems.

4.1. Autonomous Learning

As discussed in [4], the ability to recognize patterns and, more importantly, identify changes in those patterns provides substantive benefits in communications environments. It enables the ability to build patterns of behavior over the spatio-temporal environment. When coupled with sensory input, a set of temporal patterns categorized by spectrum range can be developed. This learned pattern can, in turn, be used by the radio to adapt to new or different patterns based on the method, mode, and local of deployment. The key aspect of this capability is that the learning mechanism is a straightforward combination of sensory input, event classification, and the temporal representation.

4.2. Anomalous Events

Because differences in patterns are the basis of adaptation, recognizing significant changes can be propagated to neighbor radio systems or upwards in the chain of network control. Thus, each radio provides basic sensor capabilities as part of a collaborative net of sensors that propagates and shares anomalous pattern recognition. Because of the low computational requirements of the temporal system, this capability can be deployed across a suite of small footprint sensors.

4.3. Environmental Maps

When integrated with geolocation or other positional information, a spatio-temporal map of the frequency usage can be developed. The concept of a Radio Environment Map (REM) is explored by Zhao et al in [5]. As temporal maps are built up, the patterns extracted can be exchanged with neighbors and other radio systems enabling other radio systems to share and benefit from the experiential learning of other radio nodes.

5. Summary

This paper has presented the application of temporal reasoning to a cognitive radio system. The basis of the temporal patterns is built upon a concise binary representation of temporal interval relationships. The binary representation facilitates implementation in any digital processor thereby enabling essential temporal reasoning capabilities within a cognitive radio system.

Further, the representation mechanism allows for relationships between intervals to be expressed without requiring explicit time values. This enables the radio system to develop and maintain general patterns of events and environmental sensor data. Maintaining a *temporal memory* of spectrum activity, or other events, enables the radio system to be pro-active in the reallocation and reconfiguration of resources rather than simply reacting to sensory input. This is a key extension to sensory-only methods.

Also presented was an approach to building these temporal event patterns over time. Thus the radio does not have to be pre-programmed with spectrum usage patterns., Instead, it can learn patterns of activity based on common pattern repetitions that reinforce the pattern memory.

Finally, once a temporal pattern has been established, it can be used to flag anomalous situations. As a sequence of events unfolds, it is matched to stored temporal patterns of events. As the set of events within a particular pattern are repeated, an expectation function identifies the next anticipated event. When that expectation is violated, the cognitive radio can flag it as an anomalous situation and share that knowledge with other cognitive radio systems in the vicinity.

In closing, temporal reasoning provides an opportunity for extraordinary capabilities and autonomy in a cognitive radio. Initial implementations will be incorporated within the SDR infrastructure software and preliminary empirical data will be collected and analyzed.

References

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