Conformance Testing for Interoperability of Personal Healthcare Devices

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Acknowledgement

- Our ProTest Team
  - UTA: Linbin Yu, Feng Duan
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Outline

- What is IEEE 11073 PHD?
- What is Conformance Testing?
- What is T-Way Sequence Testing?
- ProTest: A Prototype Tool (Demo)
- Conclusion and Future Work

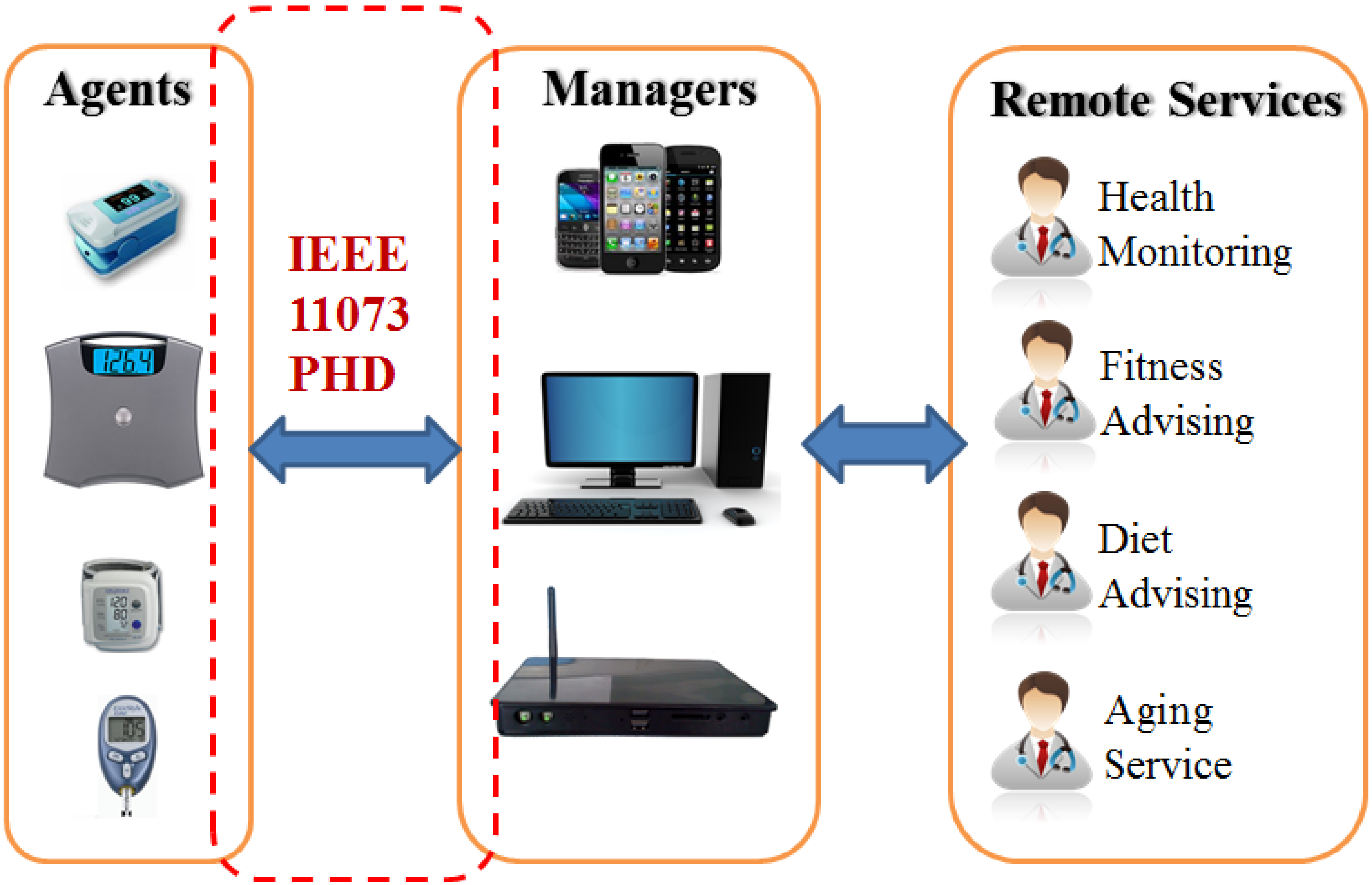
IEEE 11073 PHD

- A family of standards that allow personal healthcare devices to interoperate with each other.
- Optimized for the unique characteristics of personal healthcare devices
  - Portable, energy constrained, and limited computing capacity
- Promoted by Continua Health Alliance (http://www.continuaalliance.org/)
  - More than 200 member companies, including IBM, Intel, Cisco, Philips, Samsung, and others.

Agent and Manager

- Agent: A device used to obtain measured health data from the user.
  - blood pressure monitors, weighing scales, blood glucose monitors, and others
- Manager: Manage and process data collected by one or more agents.
  - personal computers, smart phones, set top boxes
- Manager devices are typically less powered constrained and have more computing capacity.

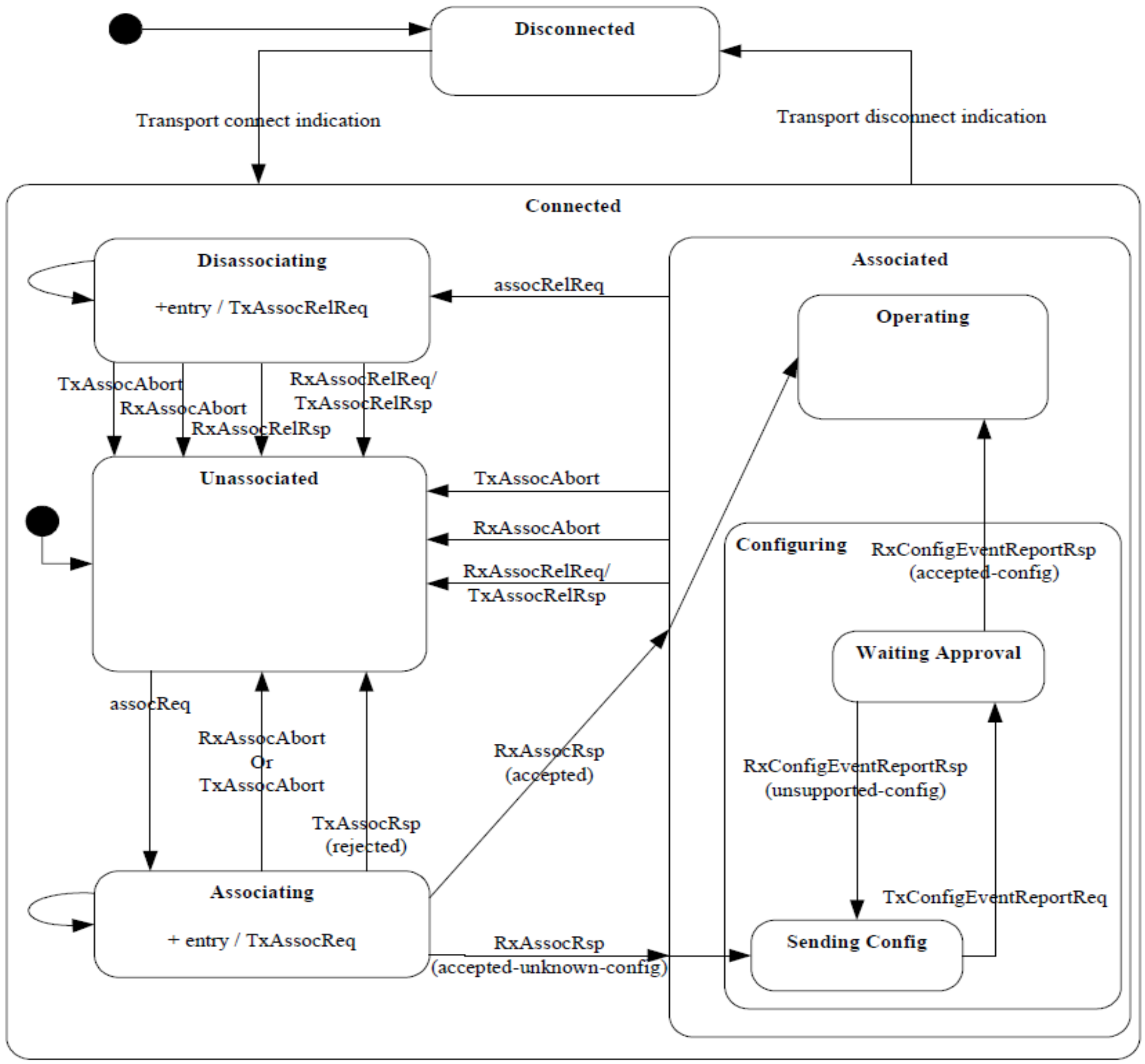
A Typical Setup



IEEE 11073-20601

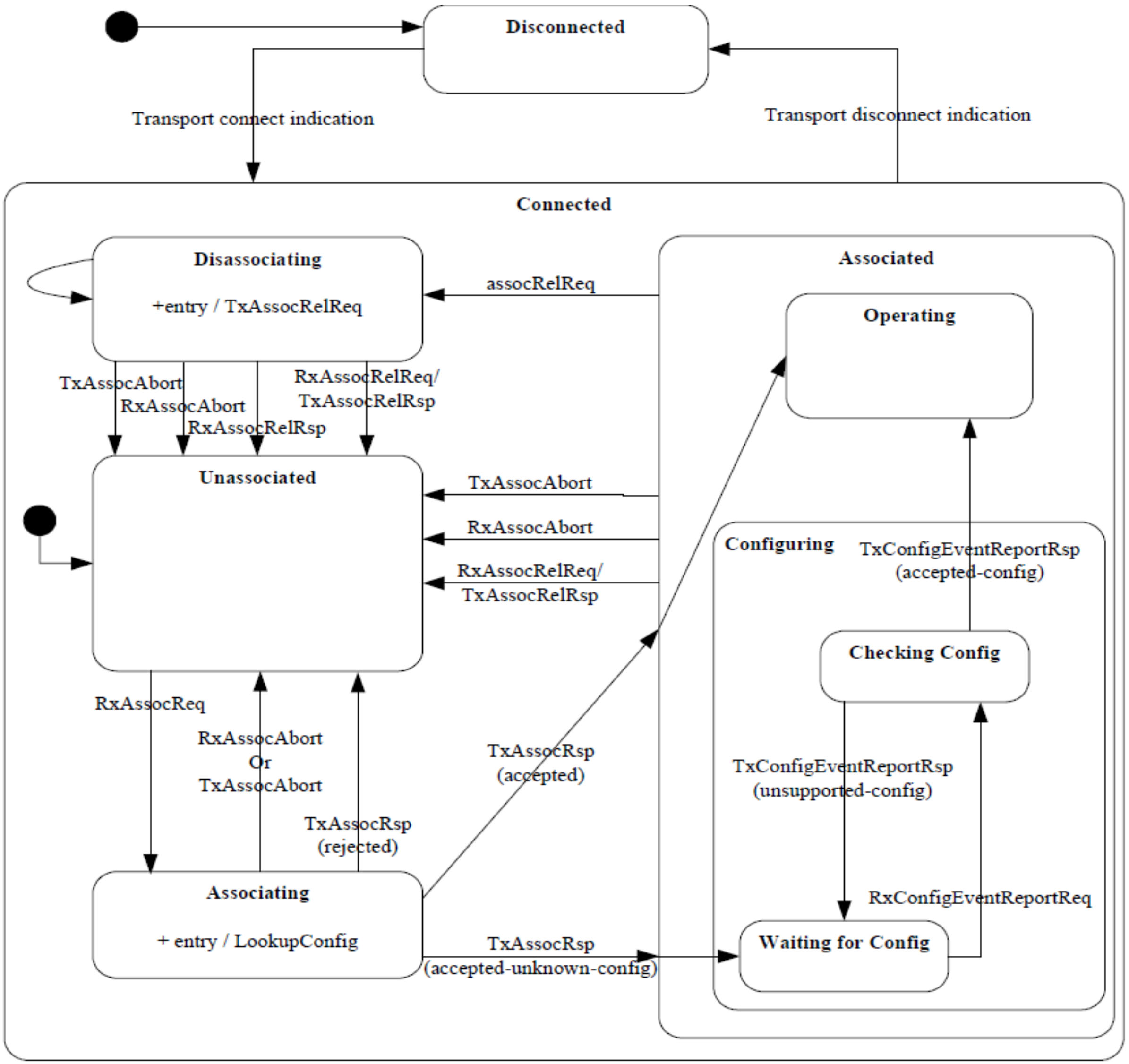
- A core component of 11073 that defines rules for data exchange between an agent and a manager.
- Defined at the application layer and can work with different transport protocols
  - Bluetooth, USB, ZigBee, and others.

The Agent State Machine



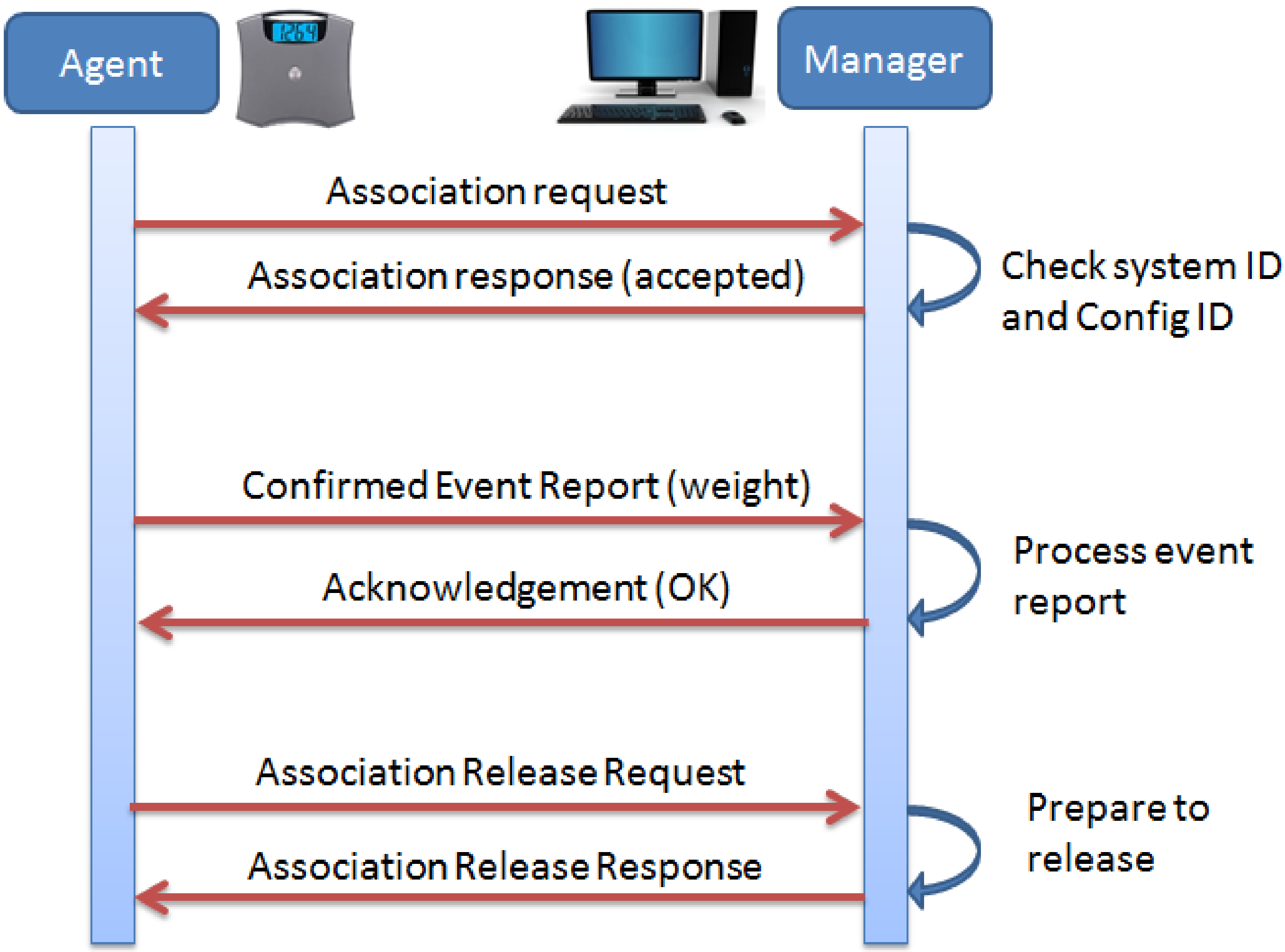
From 11073 Specification

The Manager State Machine



From 11073 Specification

An Example Scenario



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Conformance Testing

- In order for agents and managers to interoperate each other, they must implement IEEE 11073 correctly.
- Conformance testing is to test agent or manager implementations to ensure that they conform to their protocol specifications.

Testing in General

- Three major steps
  - Test generation, test execution, and test evaluation
- Often impractical to test all possible scenarios
  - What scenarios to test? When to stop?
- The key is to be systematic, i.e., follow a well-defined strategy
  - The notion of coverage is often used to ensure test adequacy
- Testing can easily take more than half of the development budget
  - This is specially so in the medical domain!

Conformance Testing in Focus

- Typically a black-box, model-based approach
  - Does not require access to source code
  - Tests are generated from a model, i.e., specification, instead of the implementation
- Multiple levels of conformance testing
  - Message level: Ensure syntactic and semantic conformance of individual messages
  - Sequence level: Ensure conformance for sequences of message exchanges.

CSE@UTA Conformance vs Interoperability

- Conformance testing typically tests individual implementations against their specifications,
- Interoperability testing actually puts multiple implementations together to see if they could interoperate with each other.
- Conformance testing can significantly increase the likelihood of interoperability

State of the Art

- Automata-Theoretic Methods: Generate test sequences to guarantee detection of certain types of errors
  - Missing transitions/states, incorrect transitions, output errors, and others
  - Impose certain assumptions and often require a large number of test sequences
  - Examples: W-method, Wp-method, UIO-method, and others

State of the Art (2)

- Coverage-Based Methods: Generate test sequences to achieve a coverage goal
  - State cover, transition cover, boundary-interior cover, and others
  - No guarantee on fault detection, but more practical in terms of assumptions and number of test sequences

Our Approach

- A coverage-based method that applies t-way testing to conformance testing of medical devices.
- T-way testing has been shown very effective for general software testing.
- Our initial results suggest that t-way testing has the promise to significantly increase the quality of conformance testing while cutting its cost.

NIST Healthcare Initiative

- Conformance Testing is a major component in the development of the core health IT Testing infrastructure led by NIST
- Specifically, our work is in the area of Conformance Testing of Medical Devices.
  - NIST tools, ICSGenerator and ValidatePDU, seem to work at the message level.
  - Our work complements them at the sequence level.

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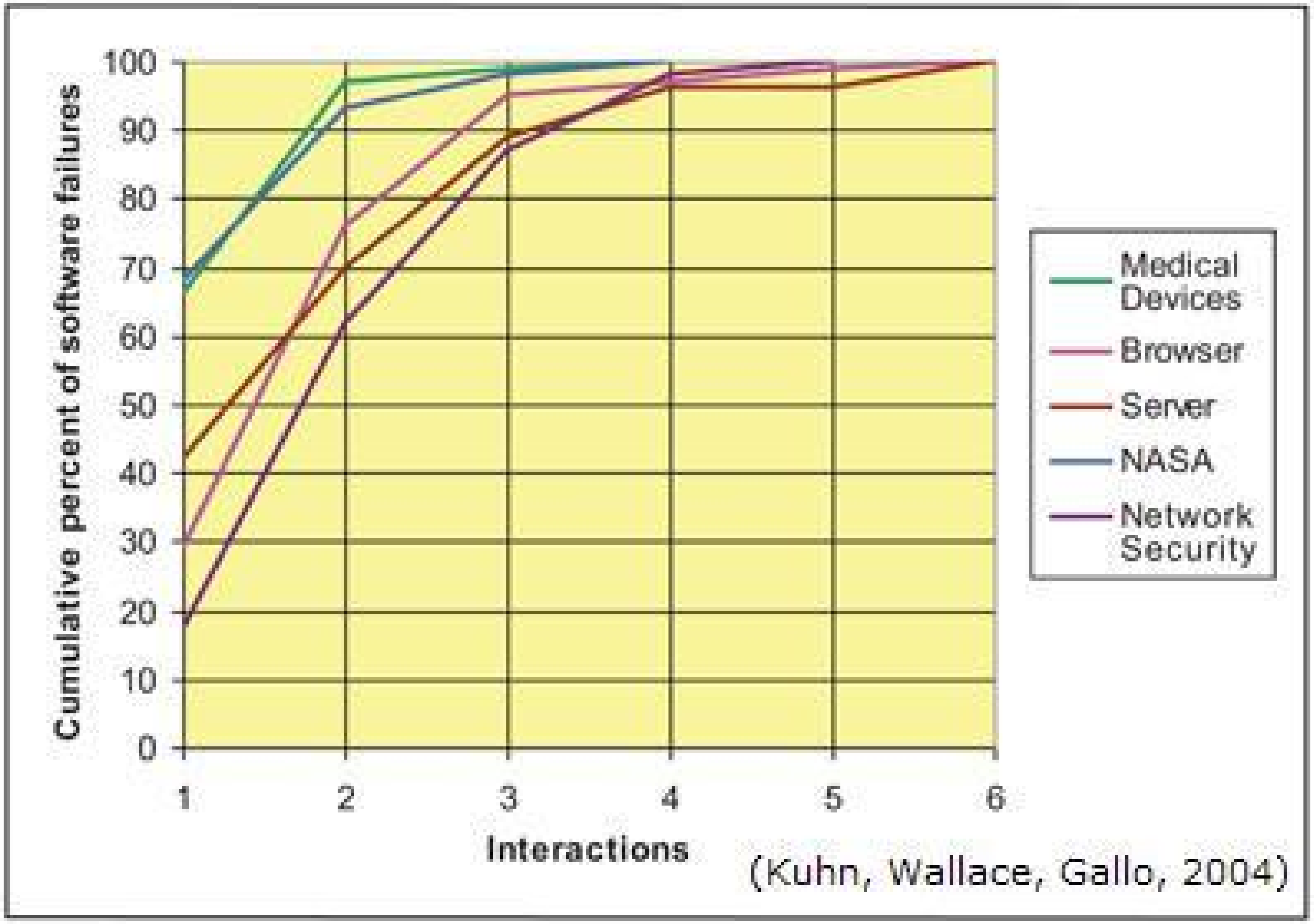
The Test Explosion Problem

- Testing is one of the most widely used approaches to ensure software quality.
- However, the number of possible tests is often huge (and even infinite)
  - About 10 million possible tests for a system with 10 5-value parameters.
- Challenge: How to select a small number of tests that are effective for fault detection?

A Bug's Perspective

- As a whole, the behavior of a system could be affected by many factors.
- However, individual bugs are often affected by only a few factors.
  - A widely-cited NIST study suggests no more than 6 factors for practical applications.
- But, we do not know "what" parameters affect "what" bugs.

The NIST Study



T-Way Testing

- A t-way test set covers all the t-way combinations, instead of all possible combinations (of all the parameters)
  - No need to know “what” parameters cause “what” faults.
- Extremely effective yet substantially reduces the number of tests
  - 10 5-value parameters (about 10M possible tests): 2-way testing – 49 tests; 3-way testing – 307 tests; 4-way testing – 1865 tests

An Example T-Way Test Set

Consider a system that has three parameters, each having two values 0 and 1.

P1	P2	P3
0	0	0
0	1	1
1	0	1
1	1	0

Pick ANY two parameters, all combinations 00, 01, 10, 11 are covered.

T-Way Sequence Testing

- Expands the domain of t-way testing from test data generation to test sequence generation
  - Order must be taken into account
- Many programs exhibit sequence-related behavior
  - Web applications, multithreaded programs, network protocols, and others
- Key Idea: Instead of testing all possible sequences of all the events, we only test all possible sequences of any t events.

T-Way Sequence Coverage

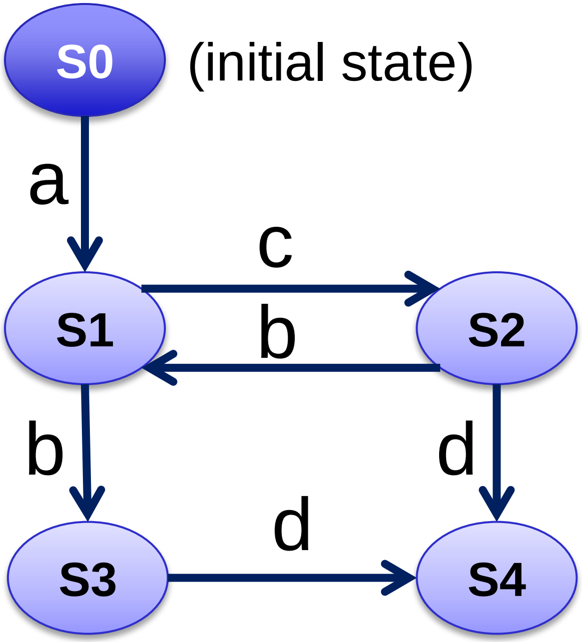
- Every t-way target sequence must be covered by at least one test sequence
  - A t-way target sequence is a sequence of t events that can be executed in the given order
  - A test sequence covers a target sequence if the t events in the target sequence are executed in the same order

T-Way Sequence Generation

a. Compute all the t-way target sequence
b. Build a shortest path P to cover a t-way target sequence
c. Extend P to cover as many target sequences as possible
d. Remove all the target sequences that are covered by P
e. Repeat steps b, c, and d until all target sequences are covered

Example

1. All 2-way target sequences:
   - ab, ac, ad, bb, bc, bd, cb, cc, cd
2. Start from S0->S1->S3 (ab), append S4: S0->S1->S3->S4
3. Build test sequence **a->b->d** which covers ab, ad, bd
4. Remaining 6 targets: ac, bb, bc, cb, cc, cd
5. Start from S0->S1->S2 (ac), build test sequence **a->c->b->b->d** and covers ac, cb, cd, bb, bd
6. Build **a->c->b->c** which covers cc
7. All targets are covered.



T-Way vs Transition Cover

- Transition cover requires every transition to be tested once
  - No attempt made to test interactions of events
- Problems due to interaction of events may not be detected by transition cover
  - For example, assume that event a affects event b, and something goes wrong with a.
  - This problem will not be detected if a and b are tested in different sequences.
- T-way testing guarantees detection of such problems!

Long vs Short Sequences

- Longer sequences can reduce the total test length as well as start-up and tear-down cost.
- However, it is often difficult to debug a long sequence if a failure is detected.
- In our approach, the length of a test sequence is restricted by allowing the same event to occur for no more than t times.

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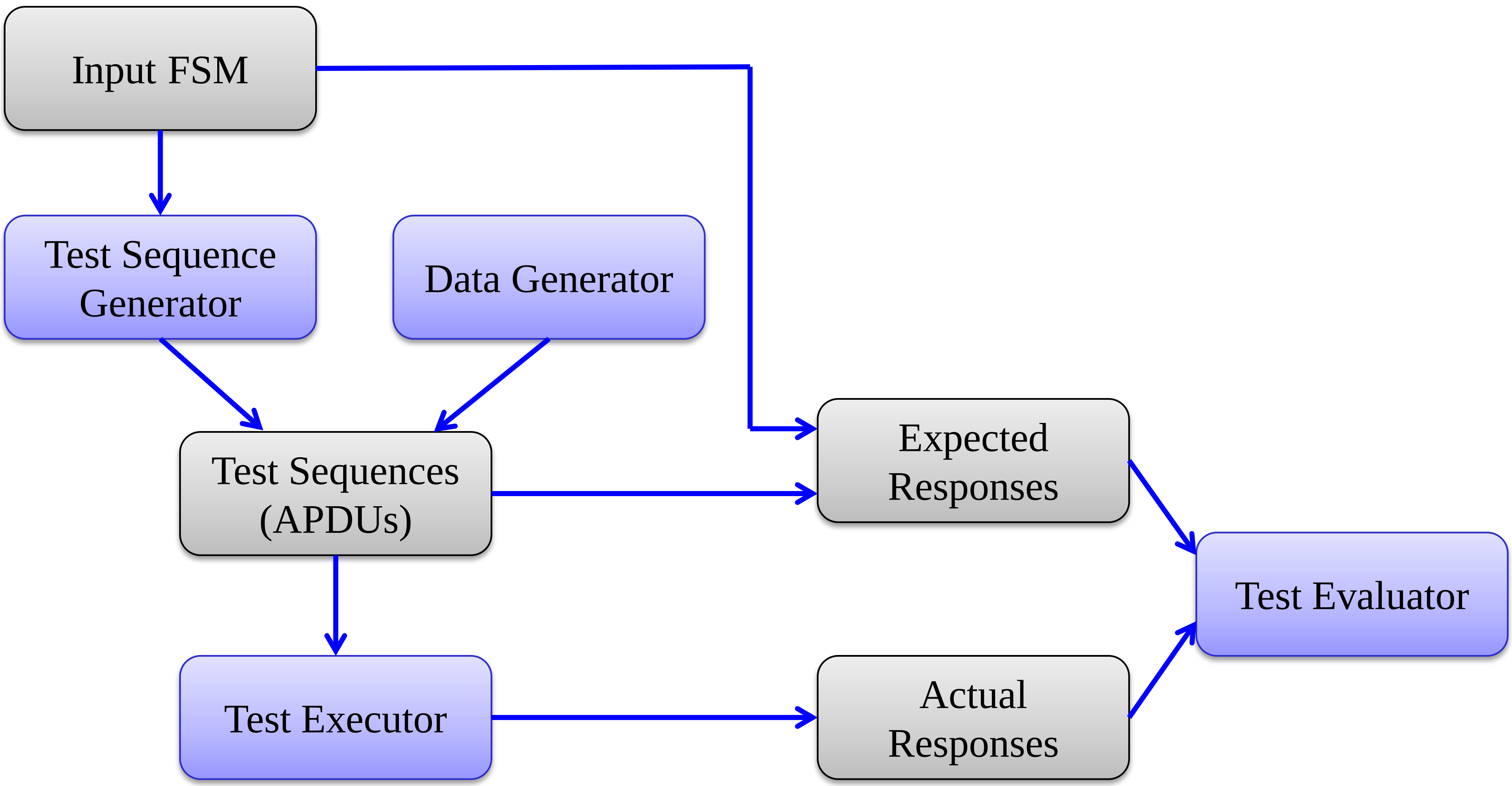
ProTest: A Prototype Tool

- Streamlines the entire testing process, and also integrates with a tool, i.e., LCOV, to collect code coverage
- Supports both transition cover and 2-way sequence testing
- Provides a GUI that allows one to easily operate, visualize and inspect the execution of test sequences
- Written in Java and thus runs on different platforms

The Framework

- Generate a set of test sequences that achieves edge or 2-way coverage based on the state machine model
- For each test sequence, generate test data that are needed to execute the sequence
  - For example, an EVENT REPORT event in a test sequence must be populated with actual report data
- Automatically execute each test sequence and then evaluate the test result

The Framework (2)



Antidote

- An open-source C implementation of 11073-20601's protocol stack
  - Mainly tested on Linux, and also has a port for Android.
  - Developed by Signove, a Connected Health company in Brazil
  - http://oss.signove.com/index.php/Antidote:_IEEE_11073-20601_stack
- Used by ProTest as the System Under Test

Other x73 Implementations

- EtherMind by Mindtree (commercial, ANSI C)
  - http://www.mindtree.com/solutions/bluetooth/ethermind-ieee-11073-stack
- OpenHealth by LibreSoft (open source, Java)
  - Mainly developed for Android
  - http://openhealth.libresoft.es/node/45
- Medical Connectivity Library by Freescale (free with Freescale processors, ANSI C)
  - http://www.freescale.com/webapp/sps/site/prod_summary.jsp?code=MEDCONLIB

Initial Results

- About 75% of statement coverage in the communications package
  – No attempt to try different message types, some transitions are not implemented
- Detected two bugs of Antidote
  – One confirmed by an Antidote developer, and the other was fixed in the latest, but not released, version
- Demonstrated that 2-way sequence testing can detect bugs that cannot be detected by state cover testing.

The Two Real Bugs

- Transition mismatch
  - A transition labeled by event rx_aarq was defined for state checking_config
  - However, in the actual code, three transitions were implemented for three sub-types of event rx_aarq_*, which can never be fired.
- Invalid message construction
  - The length of a message rx_roer was computed incorrectly, which results in a rejection by the encoding module.

A Seeded Bug

- Consider the following event sequence:
  - Agent sends an unknown but acceptable configuration
  - Manager asks for more information and then registers this configuration
  - Agent sends the same configuration again
  - Manager recognizes this configuration as a known configuration
- What if there is a bug such that Manager does not register the configuration correctly?

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Current Status

- Reported our work in a paper titled *A General Conformance Testing Framework for IEEE 11073 PHD's Communication Model*
  - To appear in the Proceedings of PETRA 2013.
- Built a project website that collects the relevant resources
  - http://barbie.uta.edu/~lyu/healthcare/
- Built a prototype tool that automates the testing process, but only for the Manager side.
- Conducted an initial study on the effectiveness of our approach.

Next Steps

- Extend ProTest to cover the Agent side
- Apply t-way testing to generate message data
  - Currently message data are generated to allow each test sequence to be executed once (i.e., no data coverage is achieved.)
- Develop a framework to allow more complex test evaluation rules
  - For example, the user may add evaluation rules based on their experience
  - Currently, we only check the response type.

Next Steps (2)

- Conduct empirical studies to evaluate our approach
  - Real-life and seeded faults, comparison with other methods, other open-source 11073 implementations
- Generalize ProTest for testing other healthcare protocols
  - Separate protocol-independent part from protocol-specific part, and provide a well-defined interface for the protocol-specific part.

Next Steps (3)

- Develop a comprehensive methodology and toolset for t-way conformance testing of healthcare protocols
  - Test data/sequence generation, and testing individual messages as well as sequence of message exchanges

Summary

- Personal health devices plays an increasingly important role in the healthcare solutions.
- Our initial results indicate that t-way testing can be very effective for testing healthcare protocols.
- Our vision is to develop a comprehensive set of t-way testing methods and tools for conformance testing of healthcare protocols.
  - Consistent with NIST’s Healthcare Initiative!

Questions?