Bayonet: Probabilistic Inference for Networks

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Abstract

Network operators often need to ensure that important probabilistic properties are met, such as that the probability of network congestion is below a certain threshold. Ensuring such properties is challenging and requires both a suitable language for probabilistic networks and an automated procedure for answering probabilistic inference queries.

We present Bayonet, a novel approach that consists of: (i) a probabilistic network programming language and (ii) a system that performs probabilistic inference on Bayonet programs. The key insight behind Bayonet is to phrase the problem of probabilistic reasoning as inference in existing probabilistic languages. As a result, Bayonet directly leverages existing probabilistic inference systems and offers a flexible and expressive interface to operators.

We present a detailed evaluation of Bayonet on common network scenarios, such as network congestion, reliability of packet delivery, and others. Our results indicate that Bayonet can express such practical scenarios and answer queries for realistic topology sizes (with up to 30 nodes).

CCS Concepts  • Mathematics of computing → Probabilistic reasoning algorithms; • Networks → Network simulations;

Keywords  Probabilistic Programming, Computer Networks

1 Introduction

Computer networks often exhibit probabilistic behaviors. Packets can get dropped because of random failures (devices or links) or congestion events. The paths that packets take are not necessarily deterministic, as network operators often employ probabilistic load-balancing techniques (e.g., ECMP [29]) to reduce network load. In addition, network traffic itself is also probabilistic – each host individually decides when, how much, and where to send packets.

There is little work in the literature on automatically reasoning about the effects of probabilistic behaviors in networks, an exception being the work of [61] (though as discussed in our related work, the two approaches differ substantially). While network simulators or emulators [11, 41, 56, 64] can be used to evaluate properties under uncertainty, their power is limited and they cannot provide statistical guarantees. Finally, many inherently deterministic network programming languages [3, 46, 53], routing protocols [49, 58], and verification tools [37, 38] require a developer to remove randomness from their assumptions, which can make the analyzed (deterministic) network models significantly different from the physical networks, rendering the analysis results inaccurate.

Key Challenges  As a result, key challenges for effective and operator-friendly analysis of networks are: (i) the design of a language that allows operators to capture practical probabilistic network scenarios and properties, and (ii) an inference system capable of automated probabilistic reasoning about these scenarios. Addressing these challenges would allow operators to more quickly experiment with various adversarial scenarios and design more robust networks.

This Work  We introduce Bayonet, a novel approach that consists of: (i) a probabilistic network programming language able to capture interesting and practical network scenarios, and (ii) a system that performs automated probabilistic inference on Bayonet programs. An important insight of Bayonet is that it phrases the problem of probabilistic network reasoning as inference in standard probabilistic programming systems, accomplished by translating Bayonet programs to probabilistic programs. This is an important insight because it allows Bayonet to directly take advantage of state-of-the-art probabilistic inference systems and...
We evaluate Bayonet (i) it abstracts away the properties (e.g., queues) a network realistic sizes: a recent analysis of 141 production networks Bayonet users and network topologies (up to 30 nodes). Our results ability of congestion, probability of correct load-balancing, common networking scenarios, such as computing the probability of network integrity properties which would be harder to achieve in general-purpose languages.

We demonstrate the use of Bayonet for two kinds of scenarios: (i) probabilistic analysis: Bayonet can either output a concrete value for Pr(S) or check if this value is within the required bounds, shown in the bottom part of the last step in Figure 1, and (ii) probabilistic synthesis: Bayonet can automatically configure the probabilistic network by first obtaining a symbolic expression for Pr(S) parameterized by the unknown symbolic configuration parameters and then infer concrete values for these parameters that satisfy the property S with a developer-specified probability. In both scenarios, we leverage the insight that probabilistic programming systems can act as powerful solvers for problems in systems and networks akin to how SMT solvers have been successfully used in program verification.

Evaluation We show that Bayonet is effective for many common networking scenarios, such as computing the probability of congestion, probability of correct load-balancing, reliability of packets, and convergence in gossip protocols. We evaluate Bayonet on different choices of inputs, schedulers and network topologies (up to 30 nodes). Our results indicate that Bayonet’s approach works for networks of realistic sizes: a recent analysis of 141 production networks indeed reported that 70% of them have 30 point-of-presences or less, each of which acting as one node [39].

Benefits over general PPL Bayonet provides three benefits over general probabilistic programming languages (PPL): (1) it checks various domain-specific integrity constraints (e.g., link queue capacities) that are harder to check in a general PPL, (2) it requires less code to express the desired functionality, and (3) it can be more easily compiled to general PPL, thus benefiting from different solvers.

Main Contributions Our main contributions are:

- The Bayonet language for specifying probabilistic interactions in networks (Sections 3.1 and 3.2).
- A query language for expressing probabilistic network properties (Section 3.3).
- The Bayonet system, which leverages state-of-the-art probabilistic inference engines by translating Bayonet programs and properties to these languages (Section 4).
- An experimental evaluation, which demonstrates the effectiveness of Bayonet on a set of 13 interesting network scenarios (Section 5).

2 Overview In this section, we demonstrate Bayonet on a simple, but illustrative example, showing how to express a non-trivial network in the language. We use this example to demonstrate how Bayonet computes probability of congestion, which occurs whenever a packet is dropped because it exceeds the capacity of a network switch. Reasoning about congestion is challenging when routers forward traffic probabilistically (e.g., for load-balancing reasons) as each packet can be forwarded along one of many possible paths. We will also show how to automatically infer network configuration parameters so as to lower this probability, effectively automating a common traffic engineering task.

2.1 Example Probabilistic Network We present the topology of our example network, along with the Bayonet programs for all network nodes (hosts and switches), in Figure 2. In this example, routers rely on the Open Shortest Path First (OSPF) protocol to compute...
point-to-point paths with minimum costs, and forward packets along these paths. If there are multiple paths with the same cost, routers load balance traffic among all of them uniformly, a widely-used load-balancing technique known as Equal-Cost MultiPath routing (ECMP). For simplicity, we assume the load-balancing decision is done for each packet individually; a per-flow decision is easy to model: since all packets in a flow have identical headers, one can simply base the decision on the hash of the packet headers.

Network Topology A network topology defines the network nodes, which can be hosts or switches, and the links that interconnect them. The network in Figure 2 has two hosts, H0 and H1, and three switches, S0, S1, and S2. Each link between nodes is represented by two ports. For instance, S0’s port pt1 and S1’s port pt1 determine the link S0→S1. Each node has an input queue, which contains packets received on the node’s input ports, and an output queue with packets to be dispatched to the node’s output ports. In our example, all queues have a capacity of 2 packets.

A packet can follow multiple paths though the network. For instance, a packet from H0 to H1 can follow the direct route S0→S1 or the route S0→S2→S1. Switch S0 compares the costs of the two routes to decide which one is followed.

Capturing Probabilistic Hosts and Switches To capture the behavior of a network node, the network operator specifies a Bayonet program, which defines how the node processes packets (e.g., program s1 defines the behavior of the switch S1). Since the network nodes read packet fields while handling packets, the operator also specifies any relevant fields, such as dst, the destination IP address of the packet.

Figure 2 presents the Bayonet programs for the five network nodes. Each program takes two inputs: pkt is the packet on top of the input queue and pt is the (integer) port on which the packet was received. A program may use the keyword state to define additional variables whose values are preserved while processing packets; e.g., at line 6, program h0 declares variable pkt_cnt and initializes it to 0. Bayonet programs manipulate packets using: new, which creates a new packet on the node’s input queue; drop, which removes the packet on top of the input queue; and fwd(pt), which forwards the packet on top of the input queue to port pt.
A program can run on a node whenever there is at least one packet in its input queue. In the beginning, there is a single packet in the input queue of host $H0$ and all other queues are empty.

We now describe the Bayonet programs associated to the hosts and switches in our example network. The Bayonet program associated with host $H0$ is declared at line 6. This program creates a new packet, sets its destination to $H1$, and sends it to port $pt1$ (which is connected to switch $S0$). The host performs this action at most three times, since it is guarded by the condition $pkt\_cnt < 3$ and $pkt\_cnt$ is increased every time a packet is sent.

The program of switch $S0$ is declared at line 24. Switch $S0$ forwards packets received on port $pt1$ to host $H0$ via port $pt3$. Packets received on port $pt2$ and destined to $H0$ are also forwarded to $H0$ via port $pt3$, while the remaining packets received on $pt2$ are forwarded to switch $S1$ via port $pt1$. If switch $S0$ receives a packet from $H0$ on port $pt3$, it forwards this packet either directly over the link $S0$→$S1$ or over link $S0$→$S2$. To decide which link to forward the packet to, the switch computes the costs associated with the two candidate routes based on the costs of the links $S0$→$S1$, $S0$→$S2$, and $S2$→$S1$ (denoted as symbolic constants $COST\_01$, $COST\_02$, and $COST\_21$). The program computes the costs of the two routes and stores the result in state variables $route1$ and $route2$; see lines 35–36. If both routes have equal costs, it randomly selects a route via a call to $flip$ (line 39). If the direct route to $S1$ has smaller cost, or it is selected by $flip$, the packet is sent to $S1$ (line 40). Otherwise, the packet is sent to $S2$ (line 42).

The remaining Bayonet programs associated to the other nodes are fairly simple: the program of switch $S1$ is analogous to that of $S0$; switch $S2$ forwards packets received from $S0$ to host $H1$; host $H1$ counts and discards received packets.

**Probabilistic Scheduling of Network Nodes** The host and switches in a real network execute asynchronously. In Bayonet, this asynchrony is captured via a probabilistic scheduler, which selects an action (a statement in a node’s program) with a specified probability. For flexibility, Bayonet allows operators to specify a probabilistic scheduler as a program written in the Bayonet language. We further discuss scheduling and specify a uniform scheduler in Section 3. In practice, the scheduler might be used to model properties of the equipment, such as link transmission delays and switch speed.

### 2.2 Analysis of Probabilistic Networks

We now show how to express probabilistic properties for networks, such as probability of congestion, and demonstrate how Bayonet automatically analyzes such properties using exact and approximate probabilistic inference engines. We discuss further properties and examples in our evaluation (Section 5).

**Expressing Relevant Properties** We first demonstrate how to express the probability of congestion for our network example in Figure 2. The probability of congestion is given by the probability that some packets are dropped due to overflowing the capacity of the queues. For our network example, this can be expressed with the query

$$\text{probability}(\text{pkt\_cnt}@H1 < 3)$$

Here, the value of $\text{pkt\_cnt}@H1$ corresponds to the number of packets received by host $H1$, as specified in its program. Since host $H0$ sends exactly 3 packets to host $H1$, if $H1$ receives less than 3 packets then congestion has occurred. The Bayonet system automatically computes that for link costs $COST\_01 = 2$, $COST\_02 = 1$, and $COST\_21 = 1$, we have

$$\text{probability}(\text{pkt\_cnt}@H1 < 3) = \frac{30378810105265}{6770637778944} \approx 0.45$$

To capture different properties, network operators can replace the predicate $S$ in the query $\text{probability}(S)$ with a predicate that specifies the property of interest.

Further, Bayonet allows operators to write queries of the form $\text{expectation}(V)$, which computes the expected value of the expression $V$. For instance, the query

$$\text{expectation}(\text{pkt\_cnt}@H1)$$

captures the expected number of packets received by host $H1$. As we will show in our evaluation section, these two types of queries enable network operators to express a range of interesting network properties, including correctness of load-balancing, reliability of packet delivery, convergence of gossip protocols, and traffic distribution.

**Answering Queries using Exact or Approximate Inference** Given a query $\text{probability}(S)$, Bayonet computes the probability that predicate $S$ is satisfied on the network’s final state (i.e., the state from which no further steps can be executed). To reason about such queries, Bayonet translates the programs associated with all network nodes into a probabilistic program (in a standard probabilistic programming language), encodes the query, and runs existing probabilistic inference engines. While most probabilistic engines are approximate [25, 26, 43], several recent systems support exact probabilistic inference [24, 52]. Bayonet leverages the power of these systems as well as any future advances (instead of reinventing them from scratch).

Concretely, our Bayonet system translates node programs to programs in the PSI language [24]; we present this translation step in Section 4. The PSI framework has the option to either perform exact symbolic inference with its own solver or to use approximate inference by translating PSI programs to WebPPL [27], a popular framework that uses approximate, sampling-based methods. Thus, Bayonet can analyze probabilistic networks using either exact solvers (especially suitable for experimenting with smaller networks and when exact results are desirable) or solvers based on approximate
To improve network utilization, such as minimizing the probability of congestion, Bayonet allows operators to define the fields necessary to specify the behavior of hosts and switches, such as id, src, dst, and protocol.

Bayesian inference (if one would like to scale the analysis to larger networks where reduced precision may be acceptable).

Bayesian Inference with Observations Bayonet supports analysis of probabilistic networks that include additional information about the state of hosts and switches. This is useful as existing network management systems routinely sample network traffic processed by switches for billing and statistics [13, 57]. With Bayonet, operators can leverage these sampled packets as observations to determine whether a given property is met or not, e.g. whether the network correctly load-balances packets along multiple paths. Specifically, network operators can encode evidence using observe statements and use Bayonet to perform classic Bayesian reasoning to answer this question (Section 5.5).

2.3 Synthesis of Network Configuration Parameters

To improve network utilization, such as minimizing the probability of congestion, operators often have to manually tailor the routers’ configurations. In our example, this means finding specific values for the symbolic constants COST 01, COST 02, and COST 21, which represent link costs.

To support this scenario, Bayonet allows network operators to leave relevant configuration parameters symbolic. By using the PSI exact solver, Bayonet can operate on symbolic constraints and output the probability of congestion (or other queries) as a function of such parameters. The resulting constraints can then be used to synthesize concrete values that optimize a given property of interest (e.g. congestion). For instance, the probability of congestion

\[ p(\text{COST}_01, \text{COST}_02, \text{COST}_21) \]

for our example which is produced by Bayonet, is given in Figure 3. The minimum congestion probability, \( \approx 0.4487 \), is obtained when the condition \( \text{COST}_01 = \text{COST}_02 + \text{COST}_21 \) holds. Note that when this condition holds, then switch 50 load-balances packets destined to H1 along the two possible paths to reach H1. Concrete values that satisfy this condition can be obtained using existing solvers, such as Mathematica or Z3 [17].

\begin{table}
\begin{tabular}{|c|c|}
\hline
Probability of congestion & Symbolic constraint \\
\hline
3037881015265 & \( \text{COST}_01 = \text{COST}_02 + \text{COST}_21 \) \\
67706637778944 & \( \text{COST}_01 = \text{COST}_02 + \text{COST}_21 \) \\
491806403 & \( \text{COST}_01 < \text{COST}_02 + \text{COST}_21 \) \\
108391168 & \( \text{COST}_01 > \text{COST}_02 + \text{COST}_21 \) \\
2025575442161 & \( \text{COST}_01 > \text{COST}_02 + \text{COST}_21 \) \\
4231664861184 & \( \text{COST}_01 < \text{COST}_02 + \text{COST}_21 \) \\
\hline
\end{tabular}
\end{table}

Figure 3. Probability of congestion as a function of the symbolic parameters \( \text{COST}_01, \text{COST}_02, \) and \( \text{COST}_21 \).

3 The Bayonet Language

In this section, we present the Bayonet language. We first define the syntax and then describe its semantics.

3.1 Specifying Probabilistic Networks in Bayonet

We depict the syntax of the Bayonet language in Figure 4.

Network Topology We consider networks with multiple hosts and switches. We do not distinguish between hosts and switches and refer to them as (network) nodes. Each network node is uniquely identified with a natural number between 1 and \( k \) and has up to \( l \) ports. A node’s port defines an interface, which can be connected to another node’s interface. An interface is a pair \( (n, p) \), where \( n \) is a node and \( p \) is a port, and a link is a pair of two interfaces. The network topology is defined by all nodes and their links.

Packets and Queues Switches process packets based on their header fields. Bayonet allows operators to define the fields necessary to specify the behavior of hosts and switches, such as id, src, dst, and protocol.

To model the input and output queues of network nodes, we introduce packet queues \( (p, c) \), which are lists of packets \( p \) with a designated capacity \( c \). We write \( (p, c):(p_k, p_t) \) to denote a queue whose head element is \( (p_k, p_t) \), and denote the enqueue operation as:

\[ (p, c):(p_k, p_t) = \begin{cases} (p + [(p_k, p_t)], c) & \text{if length}(p) < c \\ (p, c) & \text{otherwise} \end{cases} \]

where + denotes list concatenation. Note that the enqueue operation does not modify the queue if the number of packets has reached the capacity of the queue.

Probabilistic Packet-processing Programs The behavior of hosts and switches is defined by probabilistic packet processing programs, which are programs that send and receive packets; we call these Bayonet programs. A Bayonet program takes as input a packet and outputs zero or more packets, to be forwarded to other nodes in the network. Bayonet programs are probabilistic programs that feature designated network commands, such as drop and fwd. To record information relevant to a node’s behavior, each network node may keep local state in its local variables; e.g. a switch records which of its interfaces are up since it cannot forward packets along interfaces that are down.

Along with standard arithmetic expressions, Bayonet supports expressions that draw values from probability distributions; e.g., the expression \( \text{flip} \) draws a value from a Bernoulli distribution. Drawing such values is necessary to model probabilistic events, such as link and component failures, and probabilistic load-balancing protocols, such as ECMP, which are widely used by existing switches. Furthermore, random values can be drawn to specify prior distributions on uncertain properties of the network.
We now present the semantics of Bayonet work node, where \( G \) is the initial state of the network node.

## Probabilistic Packet-processing Programs

<table>
<thead>
<tr>
<th>Variables</th>
<th>( x ) ∈ ( Vars )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables</td>
<td>( v ) ∈ ( Vals ) = ( Q )</td>
</tr>
<tr>
<td>State</td>
<td>( \sigma ) ∈ ( Vars \rightarrow Vals )</td>
</tr>
<tr>
<td>Dist</td>
<td>( dist ) ::= ( \text{flip}[\text{uniformInt}] )</td>
</tr>
<tr>
<td>AExpr</td>
<td>( e \ ::= v</td>
</tr>
<tr>
<td>BExpr</td>
<td>( b \ ::= e \Rightarrow e</td>
</tr>
<tr>
<td>Stmt</td>
<td>( s \ ::= \text{new}</td>
</tr>
<tr>
<td>Config</td>
<td>( C \ ::= (\sigma, Q_{IN}, Q_{OUT}, s) \in \text{Configs} )</td>
</tr>
</tbody>
</table>

### Local Network Node Semantics

The semantics of Bayonet programs is defined in terms of transition steps which follow the form \( C \xrightarrow{p} C' \), where \( C = (\sigma, Q_{IN}, Q_{OUT}, s) \) and \( C' = (\sigma', Q_{IN}', Q_{OUT}', s') \) are node configurations. Each step may change the state \( \sigma \) of the network node, its input \( Q_{IN} \) and output \( Q_{OUT} \) queues, and its sequence \( s \) of unexecuted statements. Further, each step \( C \xrightarrow{p} C' \) is labeled with a probability \( p \), which denotes that if the node starts at configuration \( C \) then it transitions to \( C' \) with probability \( p \).

In Figure 5, we provide the small-step semantic rules. For example, Rule L-\text{Drop} defines the meaning of statement \text{drop}: it removes the packet on top of the input queue. This step is deterministic, and it is labeled with probability 1 accordingly. Rule L-\text{Fwd} states that statement \text{fwd}(pt') moves packet \text{pkt} from input queue \( Q_{IN} \) to output queue \( Q_{OUT} \). The input port \text{pt} is changed to \text{pt'}.

The statement \text{new} enqueues a packet at the node’s input queue, and \text{dup} duplicates the packet on top of the queue. Note that statements such as \text{drop} and \text{fwd} can be applied only if the input queue \( Q_{IN} \) is nonempty. Further, the statements \text{new} and \text{dup} cannot cause the queue to exceed its capacity because the enqueue operation leaves full queues intact. The remaining rules are fairly standard.

### Global Network Semantics

The global network semantics defines how the network nodes are executed and how packets move across the network. These global steps are scheduled by a probabilistic scheduler, which selects actions of the form \( \lambda \in \{\text{RUN, FWD}\} \times \{1, \ldots, k\} \). An action \((\text{RUN}, i)\) means that the \( i \)th network node executes a number of steps of its Bayonet program, and an action \((\text{FWD}, i)\) means that a packet processed by the \( i \)th node is delivered to its destination (i.e., to some node’s input queue).

A (global) network configuration is a tuple \( (\sigma_s, C_1, \ldots, C_k) \), where \( \sigma_s \) is the state of the probabilistic scheduler, and \( C_i \) are the (local) network node configurations. Given scheduler state \( \sigma_s \) and local configurations \( C_1, \ldots, C_k \), the probability
with which the scheduler selects action $\lambda$ and updates its state to $\sigma'$ is $p_\lambda = P_\lambda(\lambda, \sigma' | \sigma, C_1, \ldots, C_k)$. The conditional distribution $P_\lambda$ is specified as a stateful probabilistic program in Psi, the probabilistic language of Bayonet’s backend. As an example, in Figure 6 we present the specification of a uniform scheduler (used in evaluation later). This scheduler creates an array of actions, appends all actions that can be executed in the current state, and returns an action selected uniformly at random. The scheduler can also keep state, introduced with the state declaration. To illustrate this option,
def scheduler() state num_actions(0) {
    actions := [: [R x R]];
    for i in [0..K) {
        if (Q_in[i].size() > 0 {
            actions := (Run,i);
        }
        if (Q_out[i].size() > 0 {
            actions := (Fwd,i);
        }
    }
    num_actions := 1;
    return actions[uniformInt(0, actions.length - 1)];
}

Figure 6. A uniform scheduler

The probability of this step equals the probability that the scheduler selects the action (Fwd, i).

Network Traces Bayonet checks properties on terminal network configurations. A configuration \( N = (\sigma_0, C_1, \ldots, C_k) \) is terminal if: (i) the input and output queues of all nodes are empty and their statements are fully evaluated, or (ii) there is a node \( i \) that is in an error state due to a failed assert.

Given an initial configuration \( N_{init} = (\sigma_0, C_1, \ldots, C_k) \), we define a network trace as \( N_{init} \xrightarrow{\lambda, p} N_m \) such that \( N_{init} \xrightarrow{\lambda, p, \lambda_1, \lambda_2, \ldots, \lambda_m} N_m, \lambda = \lambda_1, \ldots, \lambda_m, p = p_1 \cdot \ldots \cdot p_m \), and all intermediate network configurations \( N_1, \ldots, N_{m-1} \) are non-terminal. Here, each \( \lambda_j \in \{\text{Run, Fwd}\} \times [1, \ldots, k] \) is an action selected by the scheduler. We denote the set of all traces for a configuration \( N_{init} \) by \( \text{Traces}(N_{init}) \). The set is finite for any configuration \( N_{init} \) that always reaches a terminal one.

Network Configuration Probabilities The unnormalized probability of reaching a network configuration \( N \) is the aggregate of the probabilities of all traces that lead to \( N \). We define unnormalized aggregate trace semantics: \( N_{init} \xrightarrow{p} N \), where \( p = \sum_{t \in \text{Traces}(N_{init})} p_t \) such that \( t \in \text{Traces}(N_{init}) \) and \( N_{init} \xrightarrow{\lambda, p_t} N_m, \lambda = \lambda_1, \ldots, \lambda_m, p = p_1 \cdot \ldots \cdot p_m \), and all intermediate network configurations \( N_1, \ldots, N_{m-1} \) are non-terminal. Due to observation failures, \( Z \) may be lower than 1. To obtain normalized probabilities, we divide unnormalized probabilities by \( Z \). The normalized aggregate trace semantics is then given by \( N_{init} \xrightarrow{p/\ Z} N \) where \( N_{init} \xrightarrow{p} N \).

3.3 Network Properties

Bayonet allows network operators to capture network properties by evaluating expressions and conditions on the local states of network nodes. As we show in our evaluation, this is sufficient to check many practical network properties.

We depict the syntax for specifying network properties in Figure 8. To check the state of local nodes, network operators can use the expression \( x@n \) where \( x \) is a variable and \( n \) is a network node identifier. This expression is evaluated at a terminal network configuration \( N \), and returns the value of variable \( x \) at the local state of node \( n \). For example, \( \text{pkt.cnt}@H1 \) returns the value of variable \( \text{pkt.cnt} \) according to the state of host \( H1 \). Using this expression, network operators can express:

- state expressions \( e \), such as \( \text{pkt.cnt}@H1 \cdot \text{pkt.cnt}@H0 \);
- state conditions \( b \), such as \( \text{pkt.cnt}@H1 < 3 \).
Operators can specify two kinds of Bayonet queries:
- \textit{expectation}(e), which returns the expected value of expression $e$ for all non-error terminating network configurations;
- \textit{probability}(b), which returns the probability that condition $b$ holds in all terminating network configurations.

For example, the query \textit{expectation}(pkt\_cnt@H1) returns the expected number of packets (pkt\_cnt) received by host H1, and \textit{probability}(pkt\_cnt@H1 < 3) returns the probability that host H1 receives less than three packets.

4 Implementation

Bayonet supports inference with two probabilistic inference solvers: (i) Psi, which performs exact symbolic inference, and (ii) WebPPL, which performs approximate inference. To leverage these solvers, the Bayonet system translates Bayonet programs to a program in the source language of Psi, which then has the options to either use its exact inference engine or to translate to WebPPL programs.

Both inference solvers can be used to compute a concrete value for a given probability/expection query. Parameter synthesis is supported only by the exact solver. It can output a symbolic expression parameterized by network parameters (which can be instantiated to concrete values). The Bayonet system is available at: http://bayonet.ethz.ch/.

To provide an intuition for our translation process, we illustrate the translation of Bayonet programs to Psi and then show how the global network semantics is encoded as a Psi program. The entire process (translation step) is fully automated.

Translating Bayonet programs to Psi

Figure 9 presents the Bayonet program of switch $s0$ (top) taken from our network example in Section 2, and the translated version of this program in Psi (bottom). The translator declares two queues Q.in and Q.out to capture the input and, respectively, output queues of the network node. The constructor $s0$ initializes the queues and the state variables route1 and route2.

The semantics of the Bayonet program $s0$ is captured by the method run(). This method takes the pair (pkt, pt) from the input queue Q.in, capturing that statements are applied to the packet and port on top of the input queue. To capture rule S-Fwd, Bayonet translates the statements $\text{fwd}(pt')$ to Q.out.pushBack(pkt, pt'), which places the current packet and the new port pt' at the back of the output queue Q.out.

Capturing Network Semantics

In addition to translating Bayonet programs of hosts and switches, the system also generates a Psi program that captures the global network semantics. The generated Psi program for our network example is given in Figure 10.

The map \textit{programs} associates network nodes to Bayonet programs and the map \textit{links} captures the topology of the network. The method scheduler() defines the behavior of the scheduler; see Figure 6 for an example. The method step() captures the global network steps. In each step, the network executes a program at the node if the scheduler returns the
def Network {
    programs := [ 0 ⇨ h0(), 1 ⇨ s0(), ... ];
    links := [ (0, 1) ⇨ (1, 3), ... ];
    scheduler.state := ...;
    def scheduler() {}
    def step(){
        (action, node_id) := scheduler();
        if action == Run {
            programs[node_id].run();
        }
        if action == Fwd {
            (pkt, out.pt) := programs[node_id].Q_out.takeFront();
            (dst_id, dst_pt) := links[(node_id, out_pt)];
            programs[dst_id].Q_in.pushBack(pkt, dst_pt);
        }
        def terminated() {  
            repeat num_steps {  
                if !terminated() {
                    step();
                }
            }
            return (query); // query to check
        }
    }
}

Figure 10. Capturing the global network semantics

Finally, the method main() unrolls the steps performed by the network. The method step() is called whenever the network has not reached a terminal state. This is checked via a call to method terminated(), which evaluates the terminal-state condition defined in Section 3.2. The assert statement at line 24 checks that the given number of steps is sufficient, such that the network reaches a terminal state. The program then returns a concrete result to the Bayonet query (i.e., an expectation or a probability query). If the operator leaves some of the input network parameters symbolic, then the Bayonet system outputs a symbolic expression that captures the possible values of the Bayonet query in terms of these symbolic parameters.

Integrity Checking Before translating programs, Bayonet checks statically for several common problems when defining networks. The checks include that each defined node is used and assigned a proper program, that all nodes are linked and that each port is connected to only one link, that the queue capacities are non-negative, that there is at least one query declaration and that the number of steps for which to simulate the network is specified exactly once. These checks are domain-specific and were easy to implement for Bayonet programs.

Benefits of Translation Our experience is that the translation of Bayonet programs into Psi programs is fairly direct. In particular, Bayonet’s operational semantics specifies how to implement an interpreter for the language, while Psi’s expressiveness is a good match for the back-end language. This also interacts well with the ability of Psi to symbolically analyze probabilistic programs. Similarly, the translation to WebPPL is also direct (although using a different set of language primitives). Note that Bayonet can use any solver that is powerful enough to capture its semantics. Support for further solvers can be added in the future. Bayonet can provide well-motivated benchmark problems for those solvers.

We note that the resulting translated programs often have many more lines of code and are harder to read than Bayonet programs. In our experiments, Bayonet programs are two to ten times smaller than the corresponding generated PSI or WebPPL programs.

The translation approach supports the hypothesis of this paper, namely, that existing probabilistic languages are a suitable backend for more restricted domain-specific languages (DSLs), yet such DSLs are more suitable and convenient for domain experts to work with than general probabilistic languages. An interesting future work item is formally proving the correctness of such translations.

Complexity Exact inference for an arbitrary Bayonet program is a hard problem, because the Bayonet language can encode non-trivial semantic properties of Turing machines whose running time can be exponential in the number of characters of the Bayonet program. In practice, the performance of exact inference will depend on the size of the state space, as well as on the capabilities of the exact solver backend to exploit structure in the given problem instance (such that it does not need to explicitly visit all reachable program states). The size of the state space depends on the number of network nodes, links, packets, queue capacities as well as other specifics such as the exact forwarding rules used, how many executions are cut short by failing assertions and observations, and whether packets are distinguishable. In general, computing the size of the state space for a given problem instance is an interesting problem in itself. For example, in a fully-connected network topology on n nodes with k distinguishable packets and queue capacity c such that any distribution of packets into queues can be reached, there are \( \sum_{i=0}^{k} \binom{n}{i} \cdot (n-1)^i \cdot [x^i][\sum_{j=1}^{c} x^j]^{2n} \) states (\( [x^i]p(x) \) denotes the coefficient of \( x^i \) in a polynomial \( p \)).

For approximate inference, the size of the state space is less important. For programs without observations, the probability of a property can be estimated with good probabilistic guarantees using standard sampling.

If the property is very unlikely, or the program is conditioned on unlikely events (as it often happens for networks,
We used two different schedulers: (i) a uniform probabilistic query (which we describe in each benchmark’s section). We considered examples that were previously studied in the context of manual network verification [22] but also other queries, beyond those handled in prior work, including probabilistic inference using evidence and parameter synthesis.

We model several network topologies and properties: (i) probability of congestion in networks with probabilistic routing; (ii) reliability of packet delivery in the presence of probabilistic failures; (iii) expected message propagation for gossip protocols; (iv) Bayesian reasoning using observations for conformance with load-balancing policies and congestion control; and (v) parameter synthesis for congestion (described in Section 2.3). Full code for all benchmarks is available at: http://bayonet.ethz.ch/.

We used the network topologies shown in Figure 11. To showcase the scalability of Bayonet when using approximate inference, we scaled topology (b) to 30 nodes for congestion and reliability, by connecting multiple copies of topology (b) in a row, and scaled the fully-connected topology (c) to 30 nodes for gossip. Note that 30 nodes is a practical network size: a recent analysis of 141 production networks reported that 70% of them have 30 nodes or less [39].

For each benchmark, we analyzed at least one representative query (which we describe in each benchmark’s section). We used two different schedulers: (i) a uniform probabilistic scheduler described on page 8, and (ii) a deterministic scheduler that does not use random choices. For approximate inference in WePPL, we used the Sequential Monte Carlo inference method (SMC) with 1000 particles.

All benchmarks were run on an AMD EPYC 7601 Processor with 500 GB RAM.

Questions We aim to answer three research questions:

- Can Bayonet capture interesting network scenarios succinctly? To answer this question we present our implementation of the problems, including the relevant code snippets. We also discuss how the results depend on the design choices such as schedulers.
- Can Bayonet perform an efficient inference for networks of realistic size? To answer this question, we run both the exact and approximate inference for networks up to size 30, a representative size for many real networks (see above).
- Can Bayonet perform effective inference with observations? To answer this question, we focus on two problems: load balancing and reliability analysis.

For each benchmark, Table 1 presents, for both the exact (Psi) and the approximate (WePPL) inference engines, the result of the query and inference times. We also note that the code size of Bayonet is significantly smaller than the code generated for the other languages: around 50% less than Psi and around 10x less than WebPPL. In the following, we describe the benchmarks individually. We discuss scaling in Section 5.4 and inference with observations in Section 5.5.

5.1 Network Congestion for Probabilistic Routing

Network congestion can seriously degrade a network’s performance and utilization. Knowing the probability of congestion is therefore of great interest to network operators.

We measure the probability of congestion for: (i) the network example presented in Section 2 and (ii) the network shown in Figure 11(a). In both networks, routers direct traffic

![Figure 11. Network topologies used in our benchmarks](image-url)

e.g. any specific sequence of observed packets may be unlikely), accurate approximate inference becomes more challenging. To us, a combination of exact and approximate inference approaches seems to be the most promising approach for solving such instances.

As Bayonet is decoupled from the inference algorithms employed by its backends, it will automatically benefit as those algorithms improve over time.

5 Evaluation

In this section we present a detailed evaluation of our approach on a range of practically-relevant network scenarios.

**Benchmarks** We considered examples that were previously studied in the context of manual network verification [22] but also other queries, beyond those handled in prior work, including probabilistic inference using evidence and parameter synthesis.

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<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Sched.</th>
<th>Nodes</th>
<th>Exact Result</th>
<th>Exact Time</th>
<th>Approximate Result</th>
<th>Approximate Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congestion</td>
<td>uni.</td>
<td>5</td>
<td>0.4487</td>
<td>65s</td>
<td>0.4570</td>
<td>22s</td>
</tr>
<tr>
<td>Congestion</td>
<td>det.</td>
<td>5</td>
<td>1.0000</td>
<td>0.5s</td>
<td>1.0000</td>
<td>19s</td>
</tr>
<tr>
<td>Congestion</td>
<td>uni.</td>
<td>6</td>
<td>0.4441</td>
<td>595s</td>
<td>0.4650</td>
<td>29s</td>
</tr>
<tr>
<td>Congestion</td>
<td>det.</td>
<td>6</td>
<td>1.0000</td>
<td>1.4s</td>
<td>1.0000</td>
<td>21s</td>
</tr>
<tr>
<td>Congestion</td>
<td>det.</td>
<td>30</td>
<td>1.0000</td>
<td>311s</td>
<td>1.0000</td>
<td>320s</td>
</tr>
<tr>
<td>Reliability</td>
<td>uni.</td>
<td>6</td>
<td>0.9995</td>
<td>0.2s</td>
<td>0.9990</td>
<td>11s</td>
</tr>
<tr>
<td>Reliability</td>
<td>det.</td>
<td>6</td>
<td>0.9995</td>
<td>0.2s</td>
<td>1.0000</td>
<td>10s</td>
</tr>
<tr>
<td>Reliability</td>
<td>uni.</td>
<td>30</td>
<td>0.9965</td>
<td>192s</td>
<td>0.9940</td>
<td>288s</td>
</tr>
<tr>
<td>Reliability</td>
<td>det.</td>
<td>30</td>
<td>0.9965</td>
<td>240s</td>
<td>0.9980</td>
<td>304s</td>
</tr>
<tr>
<td>Gossip</td>
<td>uni.</td>
<td>4</td>
<td>3.4815</td>
<td>362s</td>
<td>3.4760</td>
<td>11s</td>
</tr>
<tr>
<td>Gossip</td>
<td>det.</td>
<td>4</td>
<td>3.4815</td>
<td>12s</td>
<td>3.4890</td>
<td>11s</td>
</tr>
<tr>
<td>Gossip</td>
<td>uni.</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>16.0020</td>
<td>312s</td>
</tr>
<tr>
<td>Gossip</td>
<td>uni.</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>23.9910</td>
<td>879s</td>
</tr>
</tbody>
</table>

Table 1. Bayonet results for our benchmarks
Whenever with a single link (colored in red) that fails with probability \( S \), this hides important information, because in practice it is often formulated in terms of reliability requirements. Calculating the probability of packet delivery is thus important.

Service-level agreements, such as "99% of all packets destined to network 10.0.1/24 are delivered," are often formulated in terms of reliability requirements. Calculating the probability of packet delivery is thus important.

5.2 Reliability of Packet Delivery

Reliability of packet delivery is defined as the probability that a given packet (or, a flow of packets) is delivered to the intended destination. Service-level agreements, such as "99% of all packets destined to network 10.0.1/24 are delivered," are often formulated in terms of reliability requirements. Calculating the probability of packet delivery is thus important.

We consider a diamond network topology (Figure 11(b)) with a single link (colored in red) that fails with probability \( P_{\text{fail}} = 1/1000 \). Host \( H_0 \) sends a packet to host \( H_1 \). Switch \( S_0 \) uses the probabilistic ECMP forwarding strategy, and thus forwards half of the \( H_0 \)'s packets to \( S_1 \) and the other half to \( S_2 \). Switch \( S_2 \) forwards packets to \( S_3 \) unless the link between \( S_2 \) and \( S_1 \) has failed, in which case \( S_2 \) drops all packets.

The Bayonet programs of switches \( S_0 \) and \( S_2 \) are given in Figure 12. The variable \( \text{arrived} \) is set to \( 1 \) whenever \( H_1 \) receives a packet. We can capture the reliability of packet delivery with the query \( \text{probability}(\text{arrived}@H_1) \).

The results for this query are given in Table 1 (rows 6–8). The scheduler does not influence the query result, because in this experiment we track a single packet. The results computed using the approximate method are close (±0.005) to those computed by the exact one.

5.3 Expected Message Propagation for Gossip Protocols

Gossip protocols are used to spread information among nodes in a randomized fashion. In each round, a node selects a neighbor at random and shares a piece of information. Gossip protocols have many practical applications. For example, Google’s Certificate Transparency project uses them to spread information about suspicious SSL certificates. An important query is to compute the expected number of nodes that received the information after a given number rounds.

We consider the network topology depicted in Figure 11(c). Node \( S_0 \) starts the process by becoming infected and sending a single packet to a random adjacent node. Each uninfected node that receives a packet becomes infected and sends two more packets to (not necessarily distinct) random adjacent nodes. The goal is to analyze the distribution of the number of nodes that will become infected in total.

In the Bayonet program of a node \( S_i \), we introduce a variable \( \text{infected}@S_i \) to represent whether it is infected. We capture the expected number of infected nodes with the query \( \text{expectation}(\sum_i \text{infected}@S_i) \). The expected number of infected nodes, computed with exact inference, is \( 94/27 \approx 3.4815 \) (for both schedulers); see Table 1. As before, the approximate procedure computes results that are close to the exact one.

5.4 Performance and Network Size

To test scalability of Bayonet’s exact and approximate inference, we analyzed the computation with networks of a larger size (up to 30). Table 1 presents the performance of both exact and approximate inferences.

For congestion and reliability, both exact and approximate inference can produce results of similar accuracy within 8 minutes. For gossip, approximate inference can produce results within 11 minutes. The exact method did not terminate within an hour for these queries.

Overall, the performance results show that Bayonet is effective in analyzing non-trivial networks. Moreover, the fact that the exact solver is faster than the approximate solver for some benchmarks emphasizes the need for practical networking languages to use multiple backends.

5.5 Bayesian Reasoning using Observations

We next discuss several practical network scenarios which involve Bayesian reasoning, supported by our approach.

Probability of Correct Load-balancing

Switches that use ECMP routing compute a hash of the packet header to decide the link for forwarding the packet. Operators select a hash

---

**Figure 12.** Bayonet programs for our reliability benchmark

```
1  def h1(pkt, port)  def s2(pkt, port)
2  state arrived(0) {  state failing(2) {
3    arrived=1;  if failing == 2 {
4      drop;  failing =
5    }  flip(P_FAIL);  
6    if flip(1/2) {  
7      if failing == 1 {
8        fwd(2); // to S1  
9      } else{
10        fwd(3); // to S2  
11      }
12    }
13  }
```
function to split traffic across all outgoing links as prescribed by a load-balancing policy.

We consider the network shown in Figure 11(d). Switch $S_0$ receives traffic from $H_0$ and splits it, using ECMP, among a direct link to $H_1$ and a direct link to $S_1$. Switch $S_1$ forwards all incoming traffic to $H_1$. $S_0$, $S_1$ and $H_1$ are connected to a controller $C$, which monitors the network. There is a fixed sub-sampling probability: each node connected to the controller chooses randomly whether or not to send a copy of the packet to the controller. This way, the controller gets an incomplete, but representative picture of the network traffic.

We use Bayonet to perform Bayesian reasoning, using observations, to compute the probability that $S_0$’s hash function is bad (captured by $\text{probability}(\text{bad hash}=1)$). We first choose a prior probability on two models of $S_0$’s forwarding behavior. We believe it is likely (probability 9/10) that $S_0$ splits the traffic equally, forwarding a packet to host $H_1$ with probability 1/2. However, we are aware of the less likely scenario (probability 1/10) where $S_0$’s hash function is bad, forwarding a packet to host $H_1$ with a probability of only 1/3. The prior is therefore a Bernoulli(1/10) random variable specifying whether the hash is bad. This prior is encoded as a simple generative model and is part of the Bayonet program:

```python
def s1() state num_arr(0){
    num_arr = num_arr+1;
    if num_arr==1 { observe(pkt.id==1); }
    else if num_arr==2 { observe(pkt.id==2); }
    else if num_arr==3 { observe(pkt.id==3); }
}
```

**Figure 13.** Observations added to the program of host $H_1$.

Reliability of Packet Delivery We give another example that illustrates how Bayonet is used to perform Bayesian reasoning using observations.

We adapt the reliability scenario from Section 5.2 as follows. We consider a setting where we are uncertain of the forwarding strategy implemented by switch $S_0$. A priori, we consider two equally likely hypotheses: (i) $S_0$ selects a uniform random host out of $\{S_1, S_2\}$ for each packet; we denote this strategy by $\text{rand}$. (ii) $S_0$ forwards all packets to the same host. If case (ii) applies, we also consider it equally likely that $S_0$ always forwards to $S_1$ and that $S_0$ always forwards to $S_2$; we denote these strategies by $\text{det. } S_1$ and $\text{det. } S_2$, respectively.

We consider the scenario where we can observe the packets arriving at host $H_1$. We know that three packets, numbered 1, 2, 3, have been sent from host $H_0$, and we have observed an (exhaustive) sequence of packets arriving at host $H_1$. We can use the observed sequence of packets arrived at $H_1$ to refine our knowledge of $S_0$’s forwarding strategy.

To illustrate our analysis, we consider two example observations: (i) packet 1 arrives before packet 3, while packet 2 does not arrive at all; and (ii) all three packets arrived in the same order they were sent. These two scenarios can be expressed by modifying the program of $H_1$ (Figure 13).

For the observation (1, 3), the posterior distribution output by the exact inference of Bayonet is $\text{Pr} (\text{rand}) = 0.4383$, $\text{Pr}(\text{det. } S_1) = 0.2810$, and $\text{Pr}(\text{det. } S_2) = 0.2807$.

The posterior reflects that random forwarding is less likely than deterministic forwarding. This is because the packets were not reordered, and for the random forwarding strategy, the packets are likely to be received out of order.

Further, forwarding deterministically to $S_1$ is slightly more likely than to $S_2$. The reason is that there is a small chance the link between $S_2$ and $S_3$ will fail, in which case no packets would arrive when deterministically forwarding to $S_2$.

6 Related Work We now discuss work that is most closely related to ours.

**ProbNetKAT** We start by comparing to ProbNetKAT [22] (PNK) and its recent automation [61]:

- **Automated Inference**: PNK’s approach to automation is to provide a custom analyzer for programs in its language [61], while Bayonet translates to standard probabilistic programs. This allows Bayonet to leverage a rich body of
existing work on probabilistic inference. Further, PNK does not support parameter synthesis.

- **Synchronous vs. Asynchronous:** PNK is based on a synchronous model, while Bayonet uses a stateful probabilistic scheduler. As networks are asynchronous, we believe Bayonet allows for more realistic modeling.

- **Observations:** In contrast to Bayonet, PNK does not support observe statements. While it may be possible to extend PNK with observe statements, doing so requires care to avoid issues: a direct addition of observe as in [40] can indeed invalidate the main theorem of [61].

- **History vs. State:** Bayonet models state (e.g., packet queues), while PNK does not and uses sets of packet histories. The use of state in Bayonet strikes a good balance between expressiveness and efficiency of analysis: it can capture properties such as loops, congestion, and reliability [18, 36, 42, 51] as these do not need histories. The use of state instead of histories also greatly reduces the burden on underlying probabilistic solvers. On the other side, histories allow to elegantly capture temporal properties that will require auxiliary state in Bayonet.

- **Other Differences:** PNK has a limited support for conditionals (e.g., comparing packet fields only to constants, not to other fields) and computations (e.g., cannot count the number of hops in a packet). In contrast, Bayonet supports standard conditionals, arithmetic, and assignments.

**Probabilistic Programming** Recent years have seen significant interest in probabilistic programming languages including Stan [25], PSI [24], Fabular [8], Anglican [67], Augur [63], Church [26], Venture [43] and R2 [54]. Uncertain<T> is a library that makes probabilistic programming features available inside mainstream programming languages [9, 50].

The main purpose of these systems is to simplify the development of probabilistic models. The systems support different methods for probabilistic inference, including translation to Bayesian networks (e.g., [54]), sampling (e.g., [67]), exact symbolic inference for bounded length executions with both discrete and continuous distributions [24, 52, 60], probabilistic abstract interpretation [44, 45], axiomatic methods [5, 35, 48], analysis based on probabilistic model checking [33], and other methods [6, 7, 14, 20, 31, 59]. For a survey on probabilistic programming, please see [28].

Researchers in computer networks have used Bayesian inference for problems in traffic classification [4, 15, 47, 66], security [23], and network management [34]. However, these solutions use specific inference techniques, manually tailored for a specific problem. As such, they lack generality and cannot benefit from the latest advances in the field of probabilistic inference. Also, many of the previous techniques tackle problems in data analysis rather than network-wide reasoning. In contrast, by connecting probabilistic network reasoning to standard probabilistic programming, Bayonet can directly leverage the significant effort spent in developing advanced inference algorithms and systems and benefit from recent and future advances in probabilistic analysis [1, 2, 31, 50], compilation [30, 68], and synthesis [12, 55].

**Comparison with Network Simulators** Network simulators [56, 64, 65] or emulators [11, 41] can typically operate in deterministic mode where every run produces the same result, and randomized mode, where a run produces a different result, sampled from a (uniform) pseudorandom number generator. Statistical model checkers use similar approach to refine non-deterministic into probabilistic choice [16]. Some simulators expose probabilistic choice to the users. For instance, in the NS2 network simulator, packets can have random content and the scheduler can select the next task uniformly at random. A user can sample data from standard distributions and specify potentially randomized behavior of the scheduler using C code [32]. To mirror this flexibility in specifying probabilistic behaviors, Bayonet allows a developer to use various standard distributions and randomness in data, programs, and schedulers.

**Network Analysis** Over the last few years there has been substantial interest in analysis and verification of network behaviors, both usual network protocols and software defined networking (SDN), e.g., [10, 19, 21, 38, 62]. These efforts are largely orthogonal to our work as they do not consider probabilistic behaviors.

7 Conclusion

We presented Bayonet, a novel approach for expressing and reasoning about probabilistic networks. Our approach consists of two parts: a probabilistic language capable of expressing practical network scenarios together with an automated system that performs probabilistic reasoning. A key idea behind Bayonet’s system is to phrase the problem of probabilistic network reasoning as classic probabilistic inference, accomplished by compiling Bayonet programs to standard probabilistic programs. An important benefit of this approach is that Bayonet brings state-of-the-art advances in probabilistic inference (e.g., Bayesian reasoning) to the domain of networks. We demonstrated that Bayonet can express interesting and practical network scenarios and automatically reason about useful probabilistic network properties. Based on these results, we believe that Bayonet is a solid basis for reasoning about probabilistic networks.

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