

Trickle: A Self-Regulating Algorithm for Code Propagation and Maintenance in Wireless Sensor Networks

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ABSTRACT

We present Trickle, an algorithm for propagating and maintaining code updates in wireless sensor networks. Borrowing techniques from the epidemic/gossip, scalable multicast, and wireless broadcast literature, Trickle uses a “polite gossip” policy, where motes periodically broadcast a code summary to local neighbors but stay quiet if they have recently heard a summary identical to theirs. When a mote hears an older summary than its own, it broadcasts an update. Instead of flooding a network with packets, the algorithm controls the send rate so each mote hears a small trickle of packets, just enough to stay up to date. We show that with this simple mechanism, Trickle can scale to thousand-fold changes in network density, propagate new code in the order of seconds, and impose a maintenance cost on the order of a few sends an hour.

1. INTRODUCTION

Composed of large numbers of small, resource constrained computing nodes (“motes”), sensor networks often must operate unattended for months or years. As requirements and environments evolve in lengthy deployments, users need to be able to introduce new code to re-task a network. The scale and embedded nature of these systems – buried in bird burrows or collared on roving herds of zebras for months or years – requires network code propagation. Networking has a tremendous energy cost, however, and defines the system lifetime: laptops can be recharged, but sensor networks die. An effective reprogramming protocol must send few packets.

While code is propagating, a network can be in a useless state due to there being multiple programs running concurrently. Transition time is wasted time, and wasted time is wasted energy. Therefore, an effective reprogramming protocol must also propagate new code quickly.

The cost of transmitting new code must be measured against the duty cycle of an application. For some applications, sending a binary image (tens of kilobytes) can have the same cost as days of operation. Some sensor network applications, such as Tiny Diffusion [8], Maté [13], and TinyDB [18], use concise, high-level virtual code representations to reduce this cost. In these applications, programs are 20-400 bytes long, a handful of packets.

Wireless sensor networks may operate at a scale of hundreds, thousands, or more. Unlike Internet based systems, which represent a wide range of devices linked through a common network protocol, sensor networks are independent, application specific deployments. They exhibit highly transient loss patterns that are susceptible to changes in environmental conditions [22]. Asymmetric links are common, and prior work has shown network behavior to often be worse indoors than out, predominantly due to multi-path effects [23]. Motes come and go, due to temporary disconnections, failure, and network repopulation. As new code must eventually propagate to every mote in a network, but network membership is not static, propagation must be a continuous effort.

Propagating code is costly; learning *when* to propagate code is even more so. Motes must periodically communicate to learn when there is new code. To reduce energy costs, motes can transmit metadata to determine when code is needed. Even for binary images, this periodic metadata exchange overwhelms the cost of transmitting code when it is needed. Sending a full TinyDB binary image (≈ 64 KB) costs approximately the same as transmitting a forty byte metadata summary once a minute for a day. In Maté, Tiny Diffusion, Tiny DB, and similar systems, this tradeoff is even more pronounced: sending a few metadata packets costs the same as sending an entire program. The communication to learn when code is needed overwhelms the cost of actually propagating that code.

The first step towards sensor network reprogramming, then, is an efficient algorithm for determining when motes should propagate code, which can be used to trigger the actual code transfer. Such an algorithm has three needed properties:

Low Maintenance: When a network is in a stable state, metadata exchanges should be infrequent, just enough to ensure that the network has a single program. The transmission rate should be configurable to meet an application energy budget; this can vary from transmitting once a minute to every few hours.

Rapid Propagation: When the network discovers motes that need updates, code must propagate rapidly. Propagation should not take more than a minute or two more than the time required for transmission, even for large networks that are tens of hops across. Code must eventually propagate to every mote.

Scalability: The protocol must maintain its other properties in wide ranges of network density, from motes having a few to hundreds of network neighbors. It cannot require *a priori* density information, as density will change due to environmental effects and node failure.

In this paper, we propose Trickle, an algorithm for code propagation and maintenance in wireless sensor networks. Borrowing techniques from the epidemic, scalable multicast, and wireless broadcast literatures, Trickle regulates itself using a local “polite gossip” to exchange code metadata (we defer a detailed discussion of Trickle with regards to this prior work to Section 6). Each mote periodically broadcasts metadata describing what code it has. However, if a mote hears gossip about identical metadata to its own, it stays quiet. When a mote hears old gossip, it triggers a code update, so the gossip can be brought up to date. To achieve both rapid propagation and a low maintenance overhead, motes adjust the length of their gossiping attention spans, communicating more often when there is new code.

Trickle meets the three requirements. It imposes a maintenance overhead on the order of a few packets an hour (which can easily be pushed lower), propagates updates across multi-hop networks in tens of seconds, and scales to thousand-fold changes in network density. In addition, it handles network repopulation, is robust to network transience, loss, and disconnection, and requires very little state (in our implementation, eleven bytes).

In Section 2, we outline the experimental methodologies of this study. In Section 3, we describe the basic primitive of Trickle and its conceptual basis. In Section 4, we present Trickle’s maintenance algorithm, evaluating its scalability with regards to network density. In Section 5, we show how the maintenance algorithm can be modified slightly to enable rapid propagation, and eval-

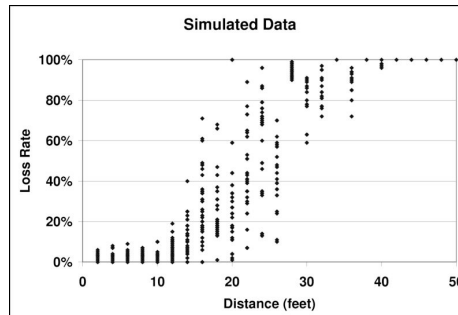


Figure 1: TOSSIM Packet Loss Rates over Distance

uate how quickly Trickle propagates code. We review related work in Section 6, and conclude in Section 7.

2. METHODOLOGY

We use three different platforms to investigate and evaluate Trickle. The first is a high-level, abstract algorithmic simulator written especially for this study. The second is TOSSIM [14], a bit-level mote simulator for TinyOS, a sensor network operating system [11]. TOSSIM compiles directly from TinyOS code. Finally, we used TinyOS mica-2 motes for empirical studies, to validate our simulation results and prove the real-world effectiveness of Trickle. The same implementation of Trickle ran on motes and in TOSSIM.

2.1 Abstract Simulation

To quickly evaluate Trickle under controlled conditions, we implemented a Trickle-specific algorithmic simulator. Little more than an event queue, it allows configuration of all of Trickle’s parameters, run duration, the boot time of motes, and a uniform packet loss rate (same for all links) across a single hop network. Its output is a packet send count.

2.2 TOSSIM

The TOSSIM simulator compiles directly from TinyOS code, simulating complete programs from application level logic to the network at a bit level [14]. It simulates the implementation of the entire TinyOS network stack, including its CSMA protocol, data encodings, CRC checks, collisions, and packet timing. TOSSIM models mote connectivity as a directed graph, where vertices are motes and edges are links; each link has a bit error rate, and as the graph is directed, link error rates can be asymmetric. This occurs when only one direction has good connectivity, a phenomenon that several empirical studies have observed [7, 23, 3]. The networking stack (based on the mica platform implementation) can handle approximately forty packets per second, with each carrying a 36 byte payload.

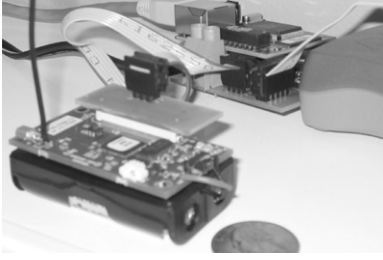


Figure 2: The TinyOS mica2

To generate network topologies, we used TOSSIM’s empirical model, based on data gathered from TinyOS motes [7]. Figure 1 shows an experiment illustrating the model’s packet loss rates over distance (in feet). As link directions are sampled independently, intermediate distances such as twenty feet commonly exhibit link asymmetry. Physical topologies are fed into the loss distribution function, producing a loss topology. In our studies, link error rates were constant for the duration of a simulation, but packet loss rates could be affected by dynamic interactions such as collisions at a receiver.

In addition to standard bit-level simulations, we used a modified version of TOSSIM that supports packet-level simulations. This version simulates loss due to packet corruption from bit errors, but does not model collisions. By comparing the results of the full bit-level simulation and this simpler packet-level simulation, we can ascertain when packet collisions – failures of the underlying MAC – are the cause of protocol behavior. In this paper, we refer to the full TOSSIM simulation as TOSSIM-bit, and the packet level simulation as TOSSIM-packet.

2.3 TinyOS motes

In our empirical experiments, we used TinyOS mica2 motes, with a 916MHz radio.¹ These motes provide 128KB of program memory, 4KB of RAM, and a 7MHz 8-bit microcontroller for a processor. The radio transmits at 19.2 Kbit, which after encoding and media access, is approximately forty TinyOS packets/second, each with a thirty-six byte data payload. For propagation experiments, we instrumented mica2 motes with a special hardware device that bridges their UART to TCP; other computers can connect to the mote with a TCP socket to read and write data to the mote. We used this to obtain millisecond granularity timestamps on network events. Figure 2 shows a picture of one of the mica2 motes used in our experiments.

We performed two empirical studies. One involved placing varying number of motes on a table, with the transmission strength set very low to create a small multi-hop network. The other was a nineteen mote network

in an office area, approximately 160’ by 40’. Section 5 presents the latter experiment in greater depth.

3. TRICKLE OVERVIEW

In the next three sections, we introduce and evaluate Trickle. In this section, we describe the basic algorithm primitive colloquially, as well as its conceptual basis. In Section 4, we describe the algorithm more formally, and evaluate the scalability of Trickle’s maintenance cost, starting with an ideal case – a lossless and perfectly synchronized single-hop network. Incrementally, we remove each of these three constraints, quantifying scalability in simulation and validating the simulation results with an empirical study. In Section 5, we show how, by adjusting the length of time intervals, Trickle’s maintenance algorithm can be easily adapted to also rapidly propagate code while imposing a minimal overhead. Trickle assumes that motes can succinctly describe their code with metadata, and by comparing two different pieces of metadata can determine which mote needs an update.

Trickle’s basic primitive is simple: every so often, a mote transmits code metadata if it has not heard a few other motes transmit the same thing. This allows Trickle to scale to thousand-fold variations in network density, quickly propagate updates, distribute transmission load evenly, be robust to transient disconnections, handle network repopulations, and impose a maintenance overhead on the order of a few packets per hour per mote.

Trickle sends all messages to the local broadcast address. There are two possible results to a Trickle broadcast: either every mote that hears the message is up to date, or a recipient detects the need for an update. Detection can be the result of either an out-of-date mote hearing someone has new code, or an updated mote hearing someone has old code. As long as every mote communicates somehow – either receives or transmits – the need for an update will be detected.

For example, if mote A broadcasts that it has code ϕ_x , but B has code ϕ_{x+1} , then B knows that A needs an update. Similarly, if B broadcasts that it has ϕ_{x+1} , A knows that it needs an update. If B broadcasts updates, then all of its neighbors can receive them without having to advertise their need. Some of these recipients might not even have heard A ’s transmission.

In this example, it does not matter who first transmits, A or B ; either case will detect the inconsistency. All that matters is that some motes communicate with one another at some nonzero rate; we will informally call this the “communication rate.” As long as the network is connected and there is some minimum communication rate for each mote, everyone will stay up to date.

The fact that communication can be either transmission or reception enables Trickle to operate in sparse as well as dense networks. A single, disconnected mote

¹There is also a 433 MHz variety.

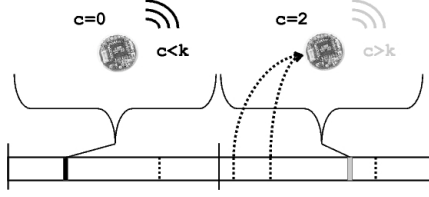


Figure 3: Trickle Maintenance with a k of 1. Dark boxes are transmissions, gray boxes are suppressed transmissions, and dotted lines are heard transmissions. Solid lines mark interval boundaries. Both I_1 and I_2 are of length τ .

must transmit at the communication rate. In a lossless, single-hop network of size n , the sum of transmissions over the network is the communication rate, so for each mote it is $\frac{1}{n}$. Sparser networks require more transmissions per mote, but utilization of the radio channel *over space* will not increase. This is an important property in wireless networks, where the channel is a valuable shared resource. Additionally, reducing transmissions in dense networks conserves system energy.

We begin in Section 4 by describing Trickle’s maintenance algorithm, which tries to keep a constant communication rate. We analyze its performance (in terms of transmissions and communication) in the idealized case of a single-hop lossless network with perfect time synchronization. We relax each of these assumptions by introducing loss, removing synchronization, and using a multi-hop network. We show how each relaxation changes the behavior of Trickle, and, in the case of synchronization, modify the algorithm slightly to accommodate.

4. MAINTENANCE

Trickle uses “polite gossip” to exchange code metadata with nearby network neighbors. It breaks time into intervals, and at a random point in each interval, it considers broadcasting its code metadata. If Trickle has already heard several other motes gossip the same metadata in this interval, it politely stays quiet: repeating what someone else has said is rude.

When a mote hears that a neighbor is behind the times (it hears older metadata), it brings everyone nearby up to date by broadcasting the needed pieces of code. When a mote hears that it is behind the times, it repeats the latest news it knows of (its own metadata); following the first rule, this triggers motes with newer code to broadcast it.

More formally, each mote maintains a counter c , a threshold k , and a timer t in the range $[0, \tau]$. k is a small, fixed integer (e.g., 1 or 2) and τ is a time constant. We discuss the selection of τ in depth in Section 5. When a mote hears metadata identical to its own, it increments c . At time t , the mote broadcasts its metadata if $c < k$.

When the interval of size τ completes, c is reset to zero and t is reset to a new random value in the range $[0, \tau]$. If a mote with code ϕ_x hears a summary for ϕ_{x-y} , it broadcasts the code necessary to bring ϕ_{x-y} up to ϕ_x . If it hears a summary for ϕ_{x+y} , it broadcasts its own summary, triggering the mote with ϕ_{x+y} to send updates.

Figure 3 has a visualization of Trickle in operation on a single mote for two intervals of length τ with a k of 1 and no new code. In the first interval, I_1 , the mote does not hear any transmissions before its t , and broadcasts. In the second interval, I_2 , it hears two broadcasts of metadata identical to its, and so suppresses its broadcast.

Using the Trickle algorithm, each mote broadcasts a summary of its data at most once per period τ . If a mote hears k motes with the same program before it transmits, it suppresses its own transmission. In perfect network conditions – a lossless, single-hop topology – there will be k transmissions every τ . If there are n motes and m non-interfering single-hop networks, there will be km transmissions, which is independent of n . Instead of fixing the per-mote send rate, Trickle dynamically regulates its send rate to the network density to meet a communication rate, requiring no a priori assumptions on the topology. In each interval τ , the sum of receptions and sends of each mote is k .

The random selection of t uniformly distributes the choice of who broadcasts in a given interval. This evenly spreads the transmission energy load across the network. If a mote with n neighbors needs an update, the expected latency to discover this from the beginning of the interval is $\frac{\tau}{n+1}$. Detection happens either because the mote transmits its summary, which will cause others to send updates, or because another mote transmits a newer summary. A large τ has a lower energy overhead (in terms of packet send rate), but also has a higher discovery latency. Conversely, a small τ sends more messages but discovers updates more quickly.

This km transmission count depends on three assumptions: no packet loss, perfect interval synchronization, and a single-hop network. We visit and then relax each of these assumptions in turn. Discussing each assumption separately allows us to examine the effect of each, and in the case of interval synchronization, helps us make a slight modification to restore scalability.

4.1 Maintenance with Loss

The above results assume that motes hear every transmission; in real-world sensor networks, this is rarely the case. Figure 4 shows how packet loss rates affect the number of Trickle transmissions per interval in a single-hop network as density increases. These results are from the abstract simulator, with $k = 1$. Each line is a uniform loss rate for all node pairs. For a given rate, the number of transmissions grows with density at $O(\log(n))$.

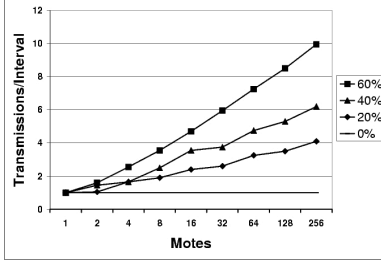


Figure 4: Number of Transmissions as Density Increases for Different Packet Loss Rates.

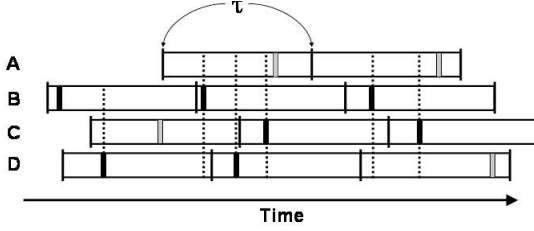


Figure 5: The Short Listen Problem For Motes A, B, C, and D. Dark bars represent transmissions, light bars suppressed transmissions, and dashed lines are receptions. Tick marks indicate interval boundaries. Mote B transmits in all three intervals.

This logarithmic behavior represents the probability that a single mote misses a number of transmissions. For example, with a 10% loss rate, there is a 10% chance a mote will miss a single packet. If a mote misses a packet, it will transmit, resulting in two transmissions. There is correspondingly a 1% chance it will miss two, leading to three transmissions, and a 0.1% chance it will miss three, leading to four. In the extreme case of a 100% loss rate, each mote is by itself: transmissions scale linearly.

Unfortunately, to maintain a per-interval minimum communication rate, this logarithmic scaling is inescapable: $O(\log(n))$ is the best-case behavior. The increase in communication represents satisfying the requirements of the worst case mote; in order to do so, the expected case must transmit a little bit more. Some motes don't hear the gossip the first time someone says it, and need it repeated. In the rest of this work, we consider $O(\log(n))$ to be the desired scalability.

4.2 Maintenance without Synchronization

The above results assume that all motes have synchronized intervals. Inevitably, time synchronization imposes a communication, and therefore energy, overhead. While some networks can provide time synchronization to Trickle, others cannot. Therefore, Trickle should be able to work in the absence of this primitive.

Unfortunately, without synchronization, Trickle can suffer from the *short-listen* problem. Some subset of motes

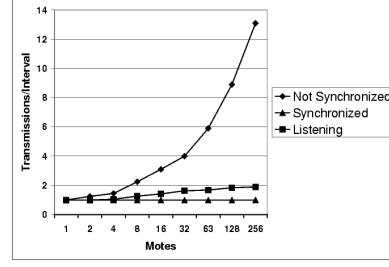


Figure 6: The Short Listen Problem's Effect on Scalability, $k = 1$. Without synchronization, Trickle scales with $O(\sqrt{n})$. A listening period restores this to asymptotically bounded by a constant.

gossip soon after the beginning of their interval, listening for only a short time, before anyone else has a chance to speak up. If all of the intervals are synchronized, the first gossip will quiet everyone else. However, if not synchronized, it might be that a mote's interval begins just after the broadcast, and it too has chosen a short listening period. This results in redundant transmissions.

Figure 5 shows an instance of this phenomenon. In this example, mote B selects a small t on each of its three intervals. Although other motes transmit, mote B never hears those transmissions before its own, and its transmissions are never suppressed. Figure 6 shows how the short-listen problem effects the transmission rate in a lossless network with $k = 1$. A perfectly synchronized single-hop network scales perfectly, with a constant number of transmissions. In a network without any synchronization between intervals, however, the number of transmissions per interval increases significantly.

The short-listen problem causes the number of transmissions to scale as $O(\sqrt{n})$ with network density.² Unlike loss, where extra $O(\log(n))$ transmissions are sent to keep the worst case mote up to date, the additional transmissions due to a lack of synchronization are completely redundant, and represent avoidable inefficiency.

To remove the short-listen effect, we modified Trickle slightly. Instead of picking a t in the range $[0, \tau]$, t is selected in the range $[\frac{\tau}{2}, \tau]$, defining a “listen-only” period of the first half of an interval. Figure 7 depicts the modified algorithm. A listening period improves scalability by enforcing a simple constraint. If sending a message guarantees a silent period of some time T that is inde-

²To see this, assume the network of n motes with an interval τ is in a steady state. If interval skew is uniformly distributed, then the expectation is that one mote will start its interval every $\frac{\tau}{n}$. For time t after a transmission, $\frac{nt}{\tau}$ will have started their intervals. From this, we can compute the expected time after a transmission that another transmission will occur. This is when

$$\prod_{t=0}^n (1 - \frac{t}{n}) < \frac{1}{2}$$

which is when $t \approx \sqrt{n}$, that is, when $\frac{\sqrt{n}}{\tau}$ time has passed. There will therefore be $O(\sqrt{n})$ transmissions.

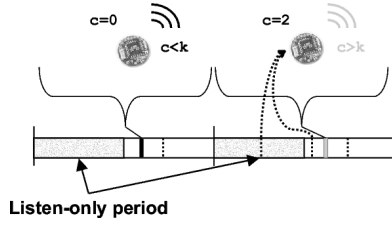


Figure 7: Trickle Maintenance with a k of 1 and a Listen-Only Period. Dark boxes are transmissions, gray boxes are suppressed transmissions, and dotted lines are heard transmissions.

pendent of density, then the send rate is bounded above (independent of the density). When a mote transmits, it suppresses all other motes for at least the length of the listening period. With a listen period of $\frac{\tau}{2}$, it bounds the total sends in a lossless single-hop network to be $2k$, and with loss scales as $2k \cdot \log(n)$, returning scalability to the $O(\log(n))$ goal.

The “Listening” line in Figure 6 shows the number of transmissions in a single-hop network with no synchronization when Trickle uses this listening period. As the network density increases, the number of transmissions per interval asymptotically approaches two. The listening period does not harm performance when the network is synchronized: there are k transmissions, but they are all in the second half of the interval.

To work properly, Trickle needs a source of randomness; this can come from either the selection of t or from a lack of synchronization. By using both sources, Trickle works in either circumstance, or any point between the two (e.g., partial or loose synchronization).

4.3 Maintenance in a Multi-hop Network

To understand Trickle’s behavior in a multi-hop network, we used TOSSIM, randomly placing motes in a 50’x50’ area with a uniform distribution, a τ of one second, and a k of 1. To discern the effect of packet collisions, we used both TOSSIM-bit and TOSSIM-packet (the former models collisions, and the latter does not). Drawing from the loss distributions in Figure 1, a 50’x50’ grid is a few hops wide. Figure 8 shows the results of this experiment.

Figure 8(a) shows how the number of transmissions per interval scales as the number of motes increases. In the absence of collisions, Trickle scales as expected, at $O(\log(n))$. This is also true in the more accurate TOSSIM-bit simulations for low to medium densities; however, once there is over 128 motes, the number of transmissions increases significantly.

This result is troubling – it suggests that Trickle cannot scale to very dense networks. However, this turns out to be a limitation of TinyOS’s CSMA as network utiliza-

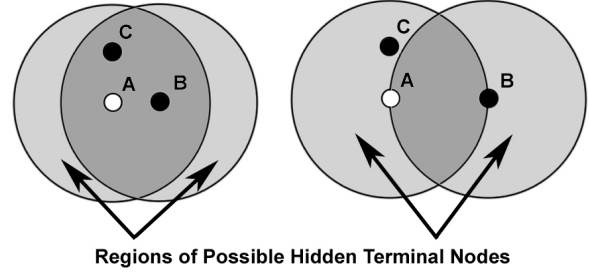


Figure 9: The Effect of Proximity on the Hidden Terminal Problem. When C is within range of both A and B , CSMA will prevent C from interfering with transmissions between A and B . But when C is in range of A but not B , B might start transmitting without knowing that C is already transmitting, corrupting B ’s transmission. Note that when A and B are farther apart, the region where C might cause this “hidden terminal” problem is larger.

tion increases, and not Trickle itself. Figure 8(b) shows the average number of receptions per transmission for the same experiments. Without packet collisions, as network density increases exponentially, so does the reception/transmission ratio. Packet collisions increase loss, and therefore the base of the logarithm in Trickle’s $O(\log(n))$ scalability. The increase is so great that Trickle’s aggregate transmission count begins to scale linearly. As the number of transmissions over space increases, so does the probability that two will collide.

As the network becomes very dense, it succumbs to the *hidden terminal problem*, a known issue with CSMA protocols. In the classic hidden terminal situation, there are three nodes, a , b , and c , with effective carrier sense between a and b and a and c . However, as b and c do not hear one another, a CSMA protocol will let them transmit at the same time, colliding at b , who will hear neither. In this situation, c is a hidden terminal to b and vice versa. Figure 9 shows an instance of this phenomenon in a simplistic disk model.

In TOSSIM-bit, the reception/transmission ratio plateaus around seventy-five: each mote thinks it has about seventy-five one-hop network neighbors. At high densities, many packets are being lost due to collisions due to the hidden terminal problem. In the perfect scaling model, the number of transmissions for m isolated and independent single-hop networks is mk . In a network, there is a *physical* density (defined by the radio range), but the hidden terminal problem causes motes to lose packets; hearing less traffic, they are aware of a smaller *observed* density. Physical density represents the number of motes who can hear a transmission in the absence of any other traffic, while observed density is a function of other, possibly conflicting, traffic in the network. Increasing physical density also make collision more likely; observed density does not necessarily increase at the same rate.

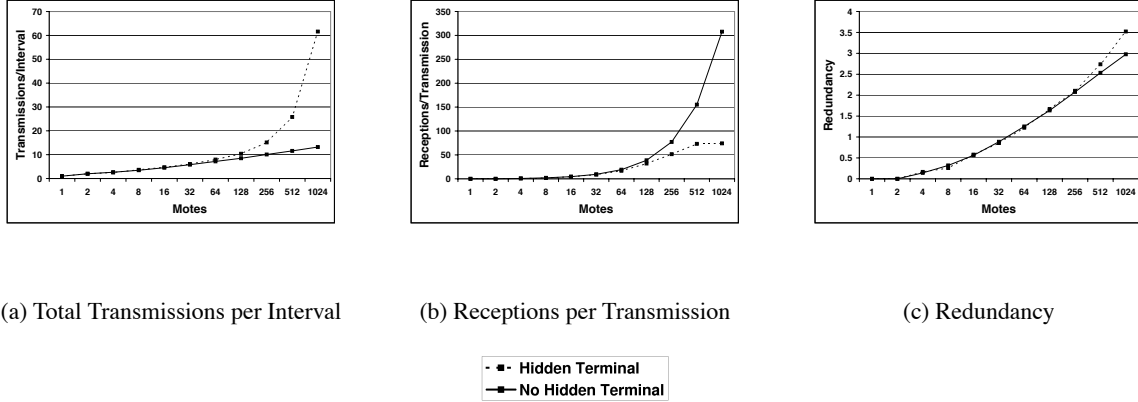


Figure 8: Simulated Trickle Scalability for a Multi-hop Network with Increasing Density. *Motes were uniformly distributed in a 50'x50' square area.*

When collisions make observed density lower than physical density, the set of motes observed to be neighbors is tied to physical proximity. The set of motes that can interfere with communication by the hidden terminal problem is larger when two motes are far away than when they are close. Figure 9 depicts this relationship.

Returning to Figure 8(b), from each mote's perspective in the 512 and 1024 mote experiments, the observed density is seventy-five neighbors. This does not change significantly as physical density increases. As a mote that can hear n neighbors, ignoring loss and other complexities, will broadcast in an interval with probability $\frac{1}{n}$, the lack of increase in observed density increases the number of transmissions (e.g., $\frac{512}{75} \rightarrow \frac{1024}{75}$).

TOSSIM simulates the mica network stack, which can handle approximately forty packets a second. As utilization reaches a reasonable fraction of this (e.g., 10 packets/second, with 128 nodes), the probability of a collision becomes significant enough to affect Trickle's behavior. As long as Trickle's network utilization is low, it scales as expected. However, increased utilization affects connectivity patterns, so that Trickle must transmit more than in a quiet network. The circumstances of Figure 8, very dense networks and a tiny interval, represent a corner case. As we present in Section 5, maintenance intervals are more likely to be on the order of tens of minutes. At these interval sizes, network utilization will never grow large as long as k is small.

To better understand Trickle in multi-hop networks, we use the metric of *redundancy*. Redundancy is the portion of messages heard in an interval that were unnecessary communication. Specifically, it is each mote's expected value of $\frac{c+s}{k} - 1$, where s is 1 if the mote transmitted and 0 if not. A redundancy of 0 means Trickle works perfectly; every mote communicates k times. For

example, a mote with a k of 2, that transmitted ($s = 1$), and then received twice ($c = 2$), would have a redundancy of 0.5 ($\frac{2+1}{2} - 1$): it communicated 50% more than the optimum of k .

Redundancy can be computed for the single-hop experiments with uniform loss (Figures 4 and 6). For example, in a single-hop network with a uniform 20% loss rate and a k of 1, 3 transmissions/interval has a redundancy of 1.4 ($((3 \cdot 0.8) - 1)$), as the expectation is that each mote receives 2.4 packets, and three motes transmit.

Figure 8(c) shows a plot of Trickle redundancy as network density increases. For a one-thousand mote—larger than any yet deployed—multi-hop network, in the presence of link asymmetry, variable packet loss, and the hidden terminal problem, the redundancy is just over 3.

Redundancy grows with a simple logarithm of the observed density, and is due to the simple problem outlined in Section 4.1: packets are lost. To maintain a communication rate for the worst case mote, the average case must communicate a little bit more. Although the communication increases, the actual per-mote transmission rate shrinks. Barring MAC failures, Trickle scales as hoped— $O(\log(n))$ —in multi-hop networks.

4.4 Load Distribution

One of the goals of Trickle is to impose a low overhead. The above simulation results show that few packets are sent in a network. However, this raises the question of which motes sent those packets; 500 transmissions evenly distributed over 500 motes does not impose a high cost, but 500 messages by one mote does.

Figure 10(a) shows the transmission distribution for a simulated 400 mote network in a 20 mote by 20 mote grid with a 5 foot spacing (the entire grid was 95'x95'), run in TOSSIM-bit. Drawing from the empirical distri-

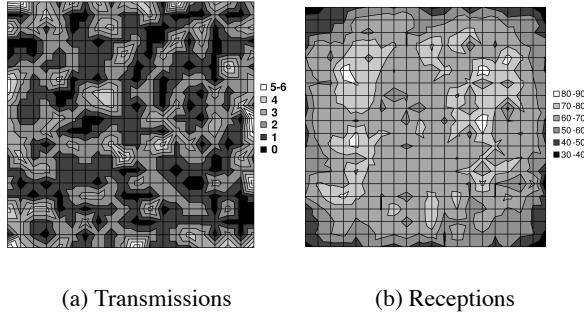


Figure 10: Communication topography of a simulated 400 mote network in a 20x20 grid with 5 foot spacing (95'x95'), running for twenty minutes with a τ of one minute. The x and y axes represent space, with motes being at line intersections. Color denotes the number of transmissions or receptions at a given mote.

butions in Figure 1, a five foot spacing forms a six hop network from grid corner to corner. This simulation was run with a τ of one minute, and ran for twenty minutes of virtual time. The topology shows that some motes send more than others, in a mostly random pattern. Given that the predominant range is one, two, or three packets, this non-uniformity is easily attributed to statistical variation. A few motes show markedly more transmissions, for example, six. This is the result of some motes being poor receivers. If many of their incoming links have high loss rates (drawn from the distribution in Figure 1), they will have a small observed density, as they receive few packets.

Figure 10(b) shows the reception distribution. Unlike the transmission distribution, this shows clear patterns. motes toward the edges and corners of the grid receive fewer packets than those in the center. This is due to the non-uniform network density; a mote at a corner has one quarter the neighbors as one in the center. Additionally, a mote in the center has many more neighbors that cannot hear one another; so that a transmission in one will not suppress a transmission in another. In contrast, almost all of the neighbors of a corner mote can hear one another. Although the transmission topology is quite noisy, the reception topography is smooth. The number of transmissions is very small compared to the number of receptions: the communication rate across the network is fairly uniform.

4.5 Empirical Study

To evaluate Trickle's scalability in a real network, we recreated, as best we could, the experiments shown in Figures 6 and 8. We placed motes on a small table, with their transmission signal strength set very low, making

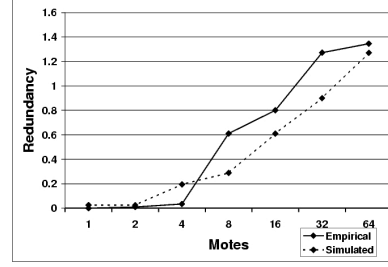


Figure 11: Empirical and Simulated over Density. The simulated data is the same as Figure 8.

Event	Action
τ Expires	Double τ , up to τ_h . Reset c , pick a new t .
t Expires	If $c < k$, transmit.
Receive same metadata	Increment c .
Receive newer metadata	Set τ to τ_l . Reset c , pick a new t .
Receive newer code	Set τ to τ_l . Reset c , pick a new t .
Receive older metadata	Send updates.

t is picked from the range $[\frac{\tau}{2}, \tau]$

Figure 12: Trickle Pseudocode.

the table a small multi-hop network. With a τ of one minute, we measured Trickle redundancy over a twenty minute period for increasing numbers of motes. Figure 11 shows the results. They show similar scaling to the results from TOSSIM-bit. For example, the TOSSIM-bit results in Figure 8(c) show a 64 mote network having an redundancy of 1.1; the empirical results show 1.35. The empirical results show that maintenance scales as the simulation results indicate it should: logarithmically.

The above results quantified the maintenance overhead. Evaluating propagation requires an implementation; among other things, there must be code to propagate. In the next section, we present an implementation of Trickle, evaluating it in simulation and empirically.

5. PROPAGATION

A large τ (gossiping interval) has a low communication overhead, but slowly propagates information. Conversely, a small τ has a higher communication overhead, but propagates more quickly. These two goals, rapid propagation and low overhead, are fundamentally at odds: the former requires communication to be frequent, while the latter requires it to be infrequent.

By dynamically scaling τ , Trickle can use its maintenance algorithm to rapidly propagate updates with a very small cost. τ has a lower bound, τ_l , and an upper bound τ_h . When τ expires, it doubles, up to τ_h . When a mote hears a summary with newer data than it has, it resets τ to be τ_l . When a mote hears a summary with older code than it has, it sends the code, to bring the other mote up to date. When a mote installs new code, it resets τ to τ_l , to make sure that it spreads quickly. This is necessary

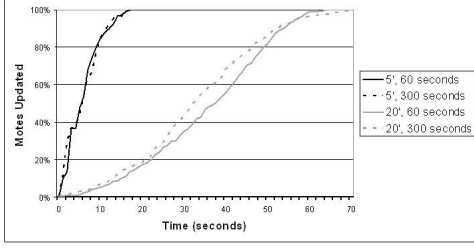


Figure 13: Simulated Code Propagation Rate for Different τ_h s.

for when a mote receives code it did not request, that is, didn't reset its τ for. Figure 12 shows pseudocode for this complete version of Trickle.

Essentially, when there's nothing new to say, motes gossip infrequently: τ is set to τ_h . However, as soon as a mote hears something new, it gossips more frequently, so those who haven't heard it yet find out. The chatter then dies down, as τ grows from τ_l to τ_h .

By adjusting τ in this way, Trickle can get the best of both worlds: rapid propagation, and low maintenance overhead. The cost of a propagation event, in terms of additional sends caused by shrinking τ , is approximately $\log(\frac{\tau_h}{\tau_l})$. For a τ_l of one second and a τ_h of one hour, this is a cost of eleven packets to obtain a three-thousand fold increase in propagation rate (or, from the other perspective, a three thousand fold decrease in maintenance overhead). The simple Trickle policy, "every once in a while, transmit unless you've heard a few other transmissions," can be used both to inexpensively maintain code and quickly propagate it.

We evaluate an implementation of Trickle, incorporated into Mat , a tiny bytecode interpreter for TinyOS sensor networks [13]. We first present a brief overview of Mat  and its Trickle implementation. Using TOSSIM, we evaluate how rapidly Trickle can propagate an update through reasonably sized (i.e., 400 mote) networks of varying density. We then evaluate Trickle's propagation rate in a small (20 mote) real-world network.

5.1 Mat , a Trickle Implementation

Mat  has a small, static set of code routines. Each routine can have many versions, but the runtime only keeps the most recent one. By replacing these routines, a user can update a network's program. Each routine fits in a single TinyOS packet and has a version number. The runtime installs routines with a newer version number when it receives them.

Instead of sending entire routines, motes can broadcast version summaries. A version summary contains the version numbers of all of the routines currently installed. A mote determines that someone else needs an update by hearing that they have an older version.

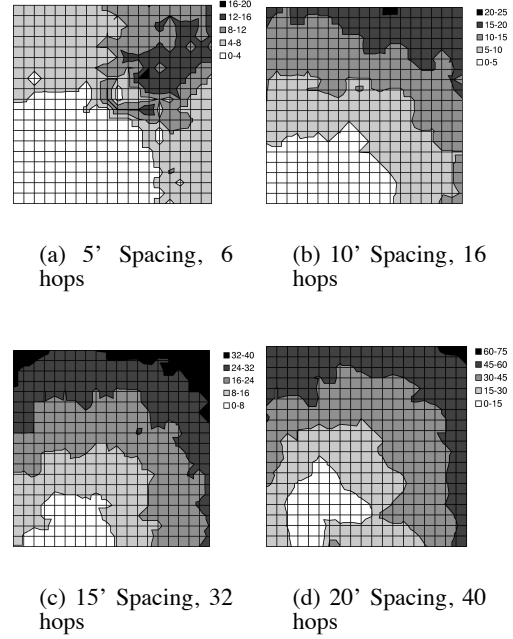


Figure 14: Simulated Time to Code Propagation Topography in Seconds. The hop count values in each legend are the expected number of transmissions necessary to get from corner to corner, considering loss.

Mat  uses Trickle to periodically broadcast version summaries. In all experiments, code routines fit in a single TinyOS packet (30 bytes). The runtime registers routines with a propagation service, which then maintains all of the necessary timers and broadcasts, notifying the runtime when it installs new code. The actual code propagation mechanism is outside the scope of Trickle, but we describe it here for completeness. When a mote hears an older vector, it broadcasts the missing routines three times: one second, three seconds, and seven seconds after hearing the vector. If code transmission redundancy were a performance issue, it could also use Trickle's suppression mechanism. For the purpose of our experiments, however, it was not.

The Mat  implementation maintains a 10Hz timer, which it uses to increment a counter. t and τ are represented in ticks of this 10Hz clock. Given that the current mote platforms can transmit on the order of 40 packets/second, we found this granularity of time to be sufficient. If the power consumption of maintaining a 10Hz clock were an issue (as it may be in some deployments), a non-periodic implementation could be used instead.

5.2 Simulation

We used TOSSIM-bit to observe the behavior of Trickle during a propagation event. We ran a series of simula-

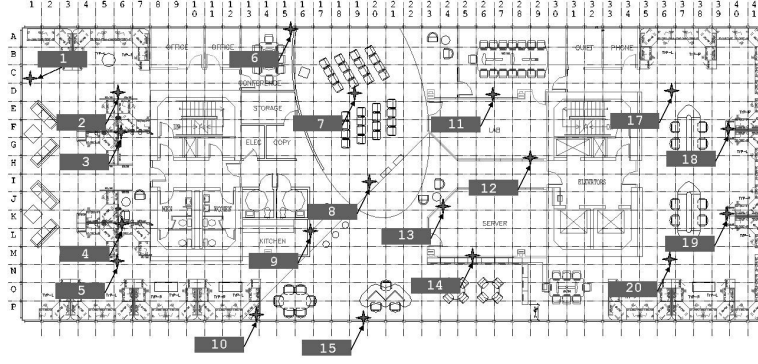
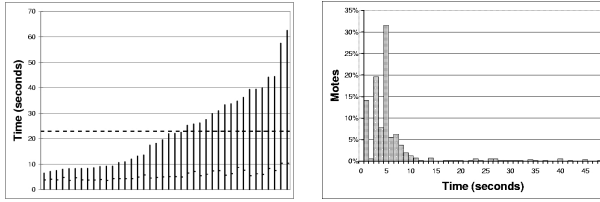
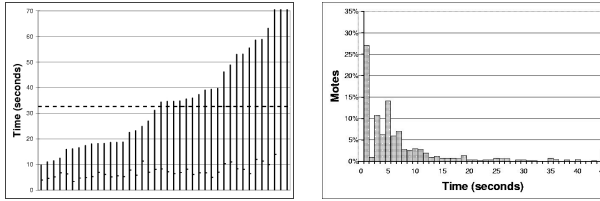


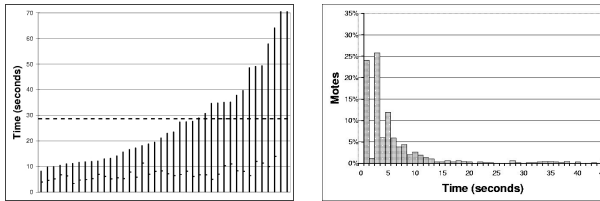
Figure 15: Empirical Testbed



(a) τ_h of 1 minute, $k = 1$



(b) τ_h of 20 minutes, $k = 1$



(c) τ_h of 20 minutes, $k = 2$

Figure 16: Empirical Network Propagation Time. The graphs on the left show the time to complete reprogramming for 40 experiments, sorted with increasing time. The graphs on the right show the distribution of individual mote reprogramming times for all of the experiments.

tions, each of which had 400 motes regularly placed in a 20x20 grid, and varied the spacing between motes. By varying network density, we could examine how Trickle's propagation rate scales over different loss rates and physical densities. Density ranged from a five foot spacing between motes up to twenty feet (the networks were 95'x95' to 380'x380'). We set τ_l to one second and τ_h to one minute. From corner to corner, these topologies range from six to forty hops.³

The simulations ran for five virtual minutes. motes booted with randomized times in the first minute, selected from a uniform distribution. After two minutes, a mote near one corner of the grid advertised a new Maté routine. We measured the propagation time (time for the last mote to install the new routine from the time it first appeared) as well as the topographical distribution of routine installation time. The results are shown in Figures 13 and 14. Time to complete propagation varied from 16 seconds in the densest network to about 70 seconds for the sparsest. Figure 13 shows curves for only the 5' and 20' grids; the 10' and 15' grid had similar curves.

Figure 14(a) shows a manifestation of the hidden terminal problem. This topography doesn't have the wave pattern we see in the experiments with sparser networks. Because the network was only a few hops in area, motes near the edges of the grid were able to receive and install the new capsule quickly, causing their subsequent transmissions to collide in the upper right corner. In contrast, the sparser networks exhibited a wave-like propagation because the sends mostly came from a single direction throughout the propagation event.

Figure 13 shows how adjusting τ_h changes the propagation time for the five and twenty foot spacings. Increasing τ_h from one minute to five does not significantly

³These hop count values come from computing the minimum cost path across the network loss topology, where each link has a weight of $\frac{1}{1-loss}$, or the expected number of transmissions to successfully traverse that link.

affect the propagation time; indeed, in the sparse case, it propagates faster until roughly the 95th percentile. This result indicates that there may be little trade-off between the maintenance overhead of Trickle and its effectiveness in the face of a propagation event.

A very large τ_h can increase the time to discover inconsistencies to be approximately $\frac{\tau_h}{2}$. However, this is only true when two stable subnets ($\tau = \tau_h$) with different code reconnect. If new code is introduced, it immediately triggers motes to τ_l , bringing the network to action.

5.3 Empirical Study

As Trickle was implemented as part of Mat  , several other services run concurrently with it. The only one of possible importance is the ad-hoc routing protocol, which periodically sends out network beacons to estimate link qualities. However, as both Trickle packets and these beacons are very infrequent compared to channel capacity (e.g., at most 1 packet/second), this does not represent a significant source of noise.

We deployed a nineteen mote network in an office area, approximately 160' by 40'. We instrumented fourteen of the motes with the TCP interface described in Section 2, for precise timestamping. When Mat   installed a new piece of code, it sent out a UART packet; by opening sockets to all of the motes and timestamping when this packet is received, we can measure the propagation of code over a distributed area.

Figure 15 shows a picture of the office space and the placement of the motes. motes 4, 11, 17, 18 and 19 were not instrumented; motes 1, 2, 3, 5, 6, 7, 8, 9, 10, 12, 13, 14, 15, and 20 were. mote 16 did not exist.

As with the above experiments, Trickle was configured with a τ_l of one second and a τ_h of one minute. The experiments began with the injection of a new piece of code through a TinyOS GenericBase, which is a simple bridge between a PC and a TinyOS network. The GenericBase broadcast the new piece of code three times in quick succession. We then logged when each mote had received the code update, and calculated the time between the first transmission and installation.

The left hand column of Figure 16 shows the results of these experiments. Each bar is a separate experiment (40 in all). The worst-case reprogramming time for the instrumentation points was just over a minute; the best case was about seven seconds. The average, shown by the dark dotted line, was just over twenty-two seconds for a τ_h of sixty seconds (Figure 16(a)), while it was thirty-two seconds for a τ_h of twenty minutes (Figure 16(b)).

The right hand column of Figure 16 shows a distribution of the time to reprogramming for individual motes across all the experiments. This shows that almost all motes are reprogrammed in the first ten seconds: the longer times in Figure 16 are from the very long tail on

this distribution. The high loss characteristics of the mote radio, combined with t 's exponential scaling, make this an issue. When scaling involves sending only a handful (e.g., $\log_2(60)$) of packets in a neighborhood in order to conserve energy, long tails are inevitable.

In Figure 16, very few motes reprogram between one and two seconds after code is introduced. This is an artifact of the granularity of the timers used, the capsule propagation timing, and the listening period. Essentially, from the first broadcast, three timers expire: $[\frac{\tau_l}{2}, \tau_l]$ for motes with the new code, $[\frac{\tau_l}{2}, \tau_l]$ for motes saying they have old code, then one second before the first capsule is sent. This is approximately $2 \cdot \frac{\tau_l}{2} + 1$; with a τ_l of one second, this latency is two seconds.

5.4 State

The Mat   implementation of Trickle requires few system resources. It requires approximately seventy bytes of RAM; half of this is a message buffer for transmissions, a quarter is pointers to the Mat   routines. Trickle itself requires only eleven bytes for its counters; the remaining RAM is used by coordinating state such as pending and initialization flags. The executable code is 2.5 KB; TinyOS's inlining and optimizations can reduce this by roughly 30%, to 1.8K. The algorithm requires few CPU cycles, and can operate at a very low duty cycle.

6. RELATED WORK

Trickle draws on two major areas of prior research. Both assume network characteristics distinct from low-power wireless sensor networks, such as cheap communication, end-to-end transport, and limited (but existing) loss. The first area is controlled, density-aware flooding algorithms for wireless and multicast networks [6, 16, 19]. The second is epidemic and gossiping algorithms for maintaining data consistency in distributed systems [2, 4, 5].

Prior work in network broadcasts has dealt with a different problem than the one Trickle tackles: delivering a piece of data to as many nodes as possible within a certain time period. Early work showed that in wireless networks, simple broadcast retransmission could easily lead to the broadcast storm problem [19], where competing broadcasts saturate the network. This observation led to work in probabilistic broadcasts [16, 21], and adaptive dissemination [9]. Just as with earlier work in bimodal epidemic algorithms [1], all of these algorithms approach the problem of making a best-effort attempt to send a message to all nodes in a network, then eventually stop.

For example, Ni et al. propose a counter-based algorithm to prevent the broadcast storm problem by suppressing retransmissions [19]. This algorithm operates on a single interval, instead of continuously. As results in Figure 16 show, the loss rates in the class of wire-

less sensor network we study preclude a single interval from being sufficient. Additionally, their studies were on lossless, disk-based network topologies; it is unclear how they would perform in the sort of connectivity observed in the real world [12].

This is insufficient for sensor network code propagation. For example, it is unclear what happens if a mote rejoins three days after the broadcast. For configurations or code, the new mote should be brought up to date. Using prior wireless broadcast techniques, the only way to do so is periodically rebroadcast to the entire network. This imposes a significant cost on the entire network. In contrast, Trickle locally distributes data where needed.

The problem of propagating data updates through a distributed system has similar goals to Trickle, but prior work has been based on traditional wired network models. Demers et al. proposed the idea of using epidemic algorithms for managing replicated databases [5], while the PlanetP project [4] uses epidemic gossiping for a distributed peer-to-peer index. Our techniques and mechanisms draw from these efforts. However, while traditional gossiping protocols use unicast links to a random member of a neighbor set, or based on a routing overlay [2], Trickle uses only a local wireless broadcast, and its mechanisms are predominantly designed to address the complexities that result.

Gossiping through the exchange of metadata is reminiscent of SPIN’s three-way handshaking protocol [9]; the Impala system, deployed in ZebraNet, uses a similar approach [15]. Specifically, Trickle is similar to SPIN-RL, which works in broadcast environments and provides reliability in lossy networks. Trickle differs from and builds on SPIN in three major ways. First, the SPIN protocols are designed for transmitting when they detect an update is needed; Trickle’s purpose is to perform that detection. Second, the SPIN work points out that periodically re-advertising data can improve reliability, but does not suggest a policy for doing so; Trickle is such a policy. Finally, the SPIN family, although connectionless, is session oriented. When a node A hears an advertisement from node B , it then requests the data from node B . In contrast, Trickle never considers addresses. Taking the previous example, with Trickle B sends an implicit request, which a node besides A may respond to.

Trickle’s suppression mechanism is inspired by the request/repair algorithm used in Scalable and Reliable Multicast (SRM) [6]. However, SRM focuses on reliable delivery of data through a multicast group in a wired IP network. Using IP multicast as a primitive, SRM has a fully connected network where latency is a concern. Trickle adapts SRM’s suppression mechanisms to the domain of multi-hop wireless sensor networks.

Although both techniques – broadcasts and epidemics – have assumptions that make them inappropriate to prob-

lem of code propagation and maintenance in sensor networks, they are powerful techniques that we draw from. An effective algorithm must adjust to local network density as controlled floods do, but continually maintain consistency in a manner similar to epidemic algorithms. Taking advantage of the broadcast nature of the medium, a sensor network can use SRM-like duplicate suppression to conserve precious transmission energy and scale to dense networks.

In the sensor network space, Reijers et al. propose energy efficient code distribution by only distributing changes to currently running code [20]. The work focuses on developing an efficient technique to compute and update changes to a code image through memory manipulation, but does not address the question of how to distribute the code updates in a network or how to validate that nodes have the right code. It is a program encoding that Trickle or a Trickle-like protocol can use to transmit updates.

The TinyDB sensor network query system uses an epidemic style of code forwarding [17]. However, it depends on periodic data collection with embedded metadata. Every tuple routed through the network has a query ID associated with it and a mote requests a new query when it hears it. In this case, the metadata has no cost, as it would be sent anyways. Also, this approach does not handle event-driven queries for rare events well; the query propagates when the event occurs, which may be too late.

7. DISCUSSION AND CONCLUSION

Using listen periods and dynamic τ values, Trickle meets the requirements set out in Section 1. It can quickly propagate new code into a network, while imposing a very small overhead. It does so using a very simple mechanism, and requires very little state. Scaling logarithmically with density, it can be used effectively in a wide range of networks. In one of our empirical experiments, Trickle imposes an overhead of less than three packets per hour, but reprograms the entire network in thirty seconds, with no effort from an end user.

A trade-off emerges between energy overhead and reprogramming rate. By using a dynamic communication rate, Trickle achieves a reprogramming rate comparable to frequent transmissions while keeping overhead comparable to infrequent transmissions. However, as Figure 16 shows, the exact relationship between constants such as τ_h and k is unclear in the context of these high loss networks. τ_l affects the head of the distribution, while τ_h affects the tail.

In this study, we have largely ignored the actual policy used to propagate code once Trickle detects the need to do so: Maté merely broadcasts code routines three times. Trickle suppression techniques can also be used to control the rate of code transmission. In the current Maté

implementation, the blind code broadcast is a form of localized flood; Trickle acts as a flood control protocol. This behavior is almost the inverse of protocols such as SPIN [9], which transmits metadata freely but controls data transmission.

Assuming complete network propagation allows Trickle to decouple code advertisement from code transmission. As the protocol does not consider network addresses, the mote that advertises code – leading to an implicit request – may not be the one that transmits it. Instead of trying to enforce suppression on an abstraction of a logical group, which can become difficult in multi-hop networks, Trickle suppresses in terms of space, implicitly defining a group. Correspondingly, Trickle does not impose the overhead of discovering and maintaining logical groups, which can be significant.

One limitation of Trickle is that it currently assumes motes are always on. To conserve energy, long-term mote deployments often have very low duty cycles (e.g., 1%). Correspondingly, motes are rarely awake, and rarely able to receive messages. Communication scheduling schemes can define times for code communication, during which motes in the network wake up to run Trickle. Essentially, the Trickle time intervals become logical time, spread over all of the periods motes are actually awake. Understandably, this might require alternative tunings of τ_h and k . Trickle’s scalability, however, stems from randomization and idle listening. As Section 4.3 showed, Trickle’s transmission scalability suffers under a CSMA protocol as utilization increases. Another, and perhaps more promising, option is to use low power listening, where transmitters send very long start symbols so receivers can detect packets when sampling the channel at a very low rate [10]. For more dense networks, the receiver energy savings could make up for the transmitter energy cost.

Trickle was designed as a code propagation mechanism over an entire network, but it has greater applicability, and could be used to disseminate any sort of data. Additionally, one could change propagation scope by adding predicates to summaries, limiting the set of motes that consider them. For example, by adding a “hop count” predicate to local routing data, summaries of a mote’s routing state could reach only two-hop network neighbors of the summary owner; this could be used to propagate copies of mote-specific information.

As sensor networks move from research to deployment, from laboratory to the real world, issues of management and reconfiguration will grow in importance. We have identified what we believe to be a core networking primitive in these systems, update distribution, and designed a scalable, lightweight algorithm to provide it.

Acknowledgements

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8. REFERENCES

- [1] K. P. Birman, M. Hayden, O. Ozkasap, Z. Xiao, M. Budiu, and Y. Minsky. Bimodal multicast. *ACM Transactions on Computer Systems (TOCS)*, 17(2):41–88, 1999.
- [2] J. Byers, J. Considine, M. Mitzenmacher, and S. Rost. Informed content delivery across adaptive overlay networks. In *Proceedings of the 2002 conference on Applications, technologies, architectures, and protocols for computer communications*, pages 47–60. ACM Press, 2002.
- [3] A. Cerpa, N. Busek, and D. Estrin. SCALE: A tool for simple connectivity assessment in lossy environments. Technical Report CENS-21, 2003.
- [4] F. M. Cuenca-Acuna, C. Peery, R. P. Martin, and T. D. Nguyen. PlanetP: Using Gossiping to Build Content Addressable Peer-to-Peer Information Sharing Communities. Technical Report DCS-TR-487, Department of Computer Science, Rutgers University, Sept. 2002.
- [5] A. Demers, D. Greene, C. Hauser, W. Irish, and J. Larson. Epidemic algorithms for replicated database maintenance. In *Proceedings of the sixth annual ACM Symposium on Principles of distributed computing*, pages 1–12. ACM Press, 1987.
- [6] S. Floyd, V. Jacobson, S. McCanne, C.-G. Liu, and L. Zhang. A reliable multicast framework for light-weight sessions and application level framing. In *Proceedings of the conference on Applications, technologies, architectures, and protocols for computer communication*, pages 342–356. ACM Press, 1995.
- [7] D. Ganesan, B. Krishnamachari, A. Woo, D. Culler, D. Estrin, and S. Wicker. An empirical study of epidemic algorithms in large scale multihop wireless networks, 2002. Submitted for publication, February 2002.
- [8] J. S. Heidemann, F. Silva, C. Intanagonwiwat, R. Govindan, D. Estrin, and D. Ganesan. Building efficient wireless sensor networks with low-level naming. In *Symposium on Operating Systems Principles*, pages 146–159, 2001.
- [9] W. R. Heinzelman, J. Kulik, and H. Balakrishnan. Adaptive protocols for information dissemination in wireless sensor networks. In *Proceedings of the fifth annual ACM/IEEE international conference on Mobile computing and networking*, pages 174–185. ACM Press, 1999.
- [10] J. Hill and D. E. Culler. Mica: a wireless platform for deeply embedded networks. *IEEE Micro*, 22(6):12–24, nov/dec 2002.
- [11] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. E. Culler, and K. S. J. Pister. System Architecture Directions for Networked Sensors. In *Architectural Support for Programming Languages and Operating Systems*, pages 93–104, 2000. TinyOS is available at <http://webs.cs.berkeley.edu>.
- [12] D. Kotz, C. Newport, and C. Elliott. The mistaken axioms of wireless-network research. Technical Report TR2003-467, Dept. of Computer Science, Dartmouth College, July 2003.
- [13] P. Levis and D. Culler. Maté: a Virtual Machine for Tiny Networked Sensors. In *Proceedings of the ACM Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, Oct. 2002.
- [14] P. Levis, N. Lee, M. Welsh, and D. Culler. TOSSIM: Simulating large wireless sensor networks of tinyos motes. In *Proceedings of the First ACM Conference on Embedded Networked Sensor Systems (SenSys 2003)*, 2003.

- [15] T. Liu and M. Martonosi. Impala: a middleware system for managing autonomic, parallel sensor systems. In *Proceedings of the ninth ACM SIGPLAN symposium on Principles and practice of parallel programming*, pages 107–118. ACM Press, 2003.
- [16] J. Luo, P. Eugster, and J.-P. Hubaux. Route driven gossip: Probabilistic reliable multicast in ad hoc networks. In *Proc. of INFOCOM 2003*, 2003.
- [17] S. R. Madden. *The Design and Evaluation of a Query Processing Architecture for Sensor Networks*. PhD thesis, UC Berkeley, December 2003. <http://www.cs.berkeley.edu/~madden/thesis.pdf>.
- [18] S. R. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong. TAG: a Tiny AGgregation Service for Ad-Hoc Sensor Networks. In *Proceedings of the ACM Symposium on Operating System Design and Implementation (OSDI)*, Dec. 2002.
- [19] S.-Y. Ni, Y.-C. Tseng, Y.-S. Chen, and J.-P. Sheu. The broadcast storm problem in a mobile ad hoc network. In *Proceedings of the fifth annual ACM/IEEE international conference on Mobile computing and networking*, pages 151–162. ACM Press, 1999.
- [20] N. Reijers and K. Langendoen. Efficient code distribution in wireless sensor networks. In *Proceedings of the Second ACM International Workshop on Wireless Sensor Networks and Applications (WSNA '03)*, 2003.
- [21] Y. Sasson, D. Cavin, and A. Schiper. Probabilistic broadcast for flooding in wireless networks. Technical Report IC/2002/54, 2002.
- [22] R. Szewczyk, J. Polastre, A. Mainwaring, and D. Culler. Lessons from a sensor network expedition. In *Proceedings of the 1st European Workshop on Wireless Sensor Networks (EWSN '04)*, January 2004.
- [23] J. Zhao and R. Govindan. Understanding packet delivery performance in dense wireless sensor networks. In *Proceedings of the First International Conference on Embedded Network Sensor Systems*, 2003.