A DTN Packet Forwarding Scheme Inspired by Thermodynamics

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***Abstract*— We study a delay tolerant network where nodes move according to heterogeneous mobility. Nodes generate messages that need to be delivered to a gateway or a sink in the network. In order to capture mobility patterns of the nodes, we introduce the notion of *temperature* for each node, which reflects the amount of messages the node can deliver towards the sink. The temperature of the nodes is governed by a set of simple rules that are analogous to the principles that govern the transfer of heat between objects. We show several desirable properties possessed by the temperature of the nodes, and based on the observations, propose a novel distributed packet forwarding scheme for DTNs.**

Index Terms: Disruption Tolerant Networks, Thermodynamics, Temperature, Wireless Networks.

I. Introduction

Disruption Tolerant Networks (DTNs) have received increasing attention in recent years, especially in military applications [2,3,6–8]. Unlike in a more traditional Mobile Adhoc NETwork (MANET) where the network is assumed to be connected most of the time, in a DTN one-hop connectivity between nodes is assumed to be sparse or, at best, the network is disconnected oftentimes. Consequently, it is unlikely that there is an end-to-end route between a source and its intended destination, e.g., a gateway or a sink. For instance, consider a military scenario in which several squadrons participate. When operating in a hostile environment, long-range communication may be either difficult to maintain due to, for example, jamming by the enemies or even undesirable when trying to avoid the detection by the enemies. Another example may be indoor environments where communication is hindered by walls and other obstacles.

In DTNs, due to lack of end-to-end routes, traditional MANET routing protocols, such as AODV [9] or DSR [4], that assume the availability of an end-to-end route are no longer applicable. Instead, nodes must exchange packets in an opportunistic manner whenever they come into contact with each other to deliver messages (also called *bundles*) to intended destinations; when two nodes meet, before an exchange of packets takes place, they first exchange a table containing the information of the packets carried by them in addition to any other control information they need. Then, they decide on the set of packets to be exchanged.

In addition to sparse connectivity, in general it is not guaranteed that every two nodes will ever meet each other. Therefore, even when infinite delay is allowed, some nodes may never be able to deliver messages directly to their destinations. As a result, nodes cannot count on a single (relay) node to deliver messages to intended destination(s), and multiple relay nodes may be needed. For the same reason, in order to increase the probability of delivery, called *packet delivery ratio*, some packet forwarding/routing schemes allow multiple copies of a packet in the network (e.g., epidemic routing [10]), at the expense of increased storage requirements at the nodes.

It is clear from above that nodes in a DTN may be required, in a distributed fashion, to choose a sequence of intermediate nodes to be traversed by messages using only *local* information when two nodes meet.[1] This suggests that, for efficient and timely delivery of messages in a DTN, when two nodes meet, they must determine the quality of the other node as a potential relay node for each message they carry. This quality as a relay node for a given destination will depend on (i) the set of other nodes the node meets and interacts with, (ii) distribution of inter-meeting times with these nodes (which determines the frequency of meetings) and distribution of meeting times (i.e., the amount of time the node spends in contact when they meet), and (iii) possibly, the quality of the channel between the nodes when they meet, which determines how quickly the nodes can exchange messages if the meeting times are short. These are mostly determined by the mobility of the nodes. Hence, the ability of the nodes to relay messages depend critically on the mobility (patterns) of the nodes.

This observation suggests that a packet forwarding scheme that allows the nodes to *learn* and *exploit* their knowledge on mobility of other nodes is likely to perform better. In this paper we propose a new framework for designing a *single-copy* packet forwarding scheme. The framework borrows an idea from thermodynamics, especially, from the way heat is exchanged between objects. We first introduce a measure, called temperature, to quantify the ability of a node to relay messages to the sink, either directly or indirectly. This measure allows our proposed scheme to learn the mobility patterns of the nodes and to create natural flows of messages from the nodes towards the sink.

The rest of the paper is organized as follows: The basic model and setup we consider are introduced in Section II.

[1]Global information would be difficult to maintain due to lack of connectivity and/or mobility of nodes.

Section III describes the key idea we borrow from thermodynamics and outlines desirable properties possessed by the temperature of the nodes. We provide simulation results in Section IV to demonstrate the potential of our new framework and the performance of our proposed scheme. Concluding remarks are given in Section V.

II. Basic model and assumptions

Consider a set $\mathcal{N} := \{1, 2, \cdots, n\}$ of mobile nodes moving on some domain $\mathbb{D}$, which is a subset of $\mathbb{R}^2$. The mobility of the nodes is allowed to be heterogeneous; the speed and support or range of the mobility may differ from one node to another. The location of node $i \in \mathbb{N}$ at time $t \geq 0$ is denoted by $\mathbf{L}_i(t)$, and the *trajectory* of node i is given by $\mathbb{L}_i := \{\mathbf{L}_i(t); t \in \mathbb{R}_+\}$, where $\mathbb{R}_+ = [0, \infty)$. Each node is assumed to generate *messages* that arrive according to some stochastic process. The messages need to be transported to a designated node known as the *information sink* or simply the *sink*. Without loss of generality we assume that the sink is node n.

We assume that a pair of nodes can communicate with each other through a *wireless* communication link if and only if their distance is smaller than or equal to a fixed communication range of the nodes, which we denote by $\gamma > 0$. Due to the mobility of the nodes, the link between two nodes, say i and j, is dynamically set up and is torn down based on the time-varying distance between them. We can model the one-hop connectivity between two nodes i and j, $i \neq j$, using an on-off process $\mathbb{C}_{ij} := \{C_{ij}(t); t \in \mathbb{R}_+\}$, where

$$C_{ij}(t) = \begin{cases} 1 & \text{if } ||L_i(t) - L_j(t)||_2 \leq \gamma \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

and $||L_i(t) - L_j(t)||_2$ is the Euclidean distance between $L_i(t)$ and $L_j(t)$. When $C_{ij}(t) = 1$, we say that nodes i and j are *in contact*. As mentioned in the previous section, in a DTN, it is unlikely that there will be a (long-lived) end-to-end route available from a node to the sink. Therefore, the nodes must forward their messages to the sink in an opportunistic manner, by relying only on *intermittent* links between nodes.

In practice, it is likely that the contact times (i.e., the amounts of time two nodes spend in contact once they meet) are much larger than the amount of time needed to complete a transfer of messages. Hence, we assume that a transfer of messages occurs (almost) instantly and the nodes can complete all necessary transfers of messages while they remain in contact.

Our goal is to find a model that can capture the *heterogeneous* mobility of nodes and allows us to design a simple, yet efficient packet forwarding scheme that exploits the knowledge of nodes' mobility. This is achieved by introducing a time-varying measure that quantifies (direct or indirect) exposure of each node to the sink (over some period), which obviously depends on nodes' mobility and frequency they visit the sink. This measure can also be viewed as an estimate of node's ability to forward messages to the sink (either directly or indirectly). It is used to guide packet forwarding decisions by the nodes when they meet. In a nutshell, when two nodes meet, messages are forwarded from the node with a smaller value to the node with a larger value. The intuition behind this is that a node with a large value is believed to have more access to the sink. Again, this access may take the form of direct access when the node meets the sink or indirect access through other relay nodes.

We first list some of properties one would expect such a measure to possess:

P1. The value of the measure lies in a compact interval. Moreover, it increases monotonically while the node is in proximity of the sink, i.e., the sink is in contact with the node.

P2. When a node moves out of the communication range of the sink, its value decreases monotonically while the node is not in contact with any other node.

P3. While two nodes are within the communication range of each other, their values are continually updated; the value of the node with a larger (resp. smaller) value decreases (resp. increases).

The first two properties are intuitive. The last property can be motivated as follows: When a node i with a smaller value comes in contact with another node j with a larger value, loosely speaking, the encounter provides node i with an opportunity to *relay* some messages through node j, increasing node i's indirect access to the sink. This type of indirect access to the sink needs to be captured when multi-hop forwarding of messages is necessary. At the same time, as node i relies on node j to carry some of node i's messages as a relay node, node j's ability to serve as a relay node to other nodes should be discounted.

III. Temperature as a measure of exposure to the sink

In this section we introduce a simple model for capturing the mobility of the nodes in the network, which is inspired by *thermodynamics*, in particular, by the way heat is exchanged between objects. In this model, each node maintains a variable called *temperature*. This temperature serves as the measure of exposure to the sink, which is described in the previous section. We denote the temperature of node $i \in \mathcal{N}$ at time $t \geq 0$ by $\theta_i(t)$, and define $\Theta_i := \{\theta_i(t); t \in \mathbb{R}_+\}$. In order to emulate the law that governs exchange of heat in a DTN, the change in temperature of the nodes follows the following simple rule:

Heat Exchange Rule: *While two nodes i and j are in contact with each other, the rate of heat change between the nodes is proportional to the difference in their temperature. In other words, the rate of change in temperature at node i, denoted by $\Delta\theta_i$, is given by*

$$\Delta\theta_i = \lambda_{ij}(\theta_j - \theta_i) \ , \ i, j \in \mathcal{N} \ , \quad (2)$$

where $\lambda_{ij} \geq 0$ is the heat exchange coefficient from node j to node i. We assume that these coefficients between two nodes

$i, j \in \mathcal{N} \setminus \{n\} =: \mathcal{N}^\star$ *are symmetric, i.e.,* $\lambda_{ij} = \lambda_{ji}$.

The aforementioned principle that guides the evolution of temperature at the nodes (through an analogy of heat exchange) is rather simple. However, in order to design a practical packet forwarding scheme based on lessons from thermodynamics, we need to introduce following additional rules and assumptions

- The temperature of the sink is $\theta_n = \theta_n(t) = T > 0$ for all $t \geq 0$. It is constant and is not affected by proximity of other nodes. This can be modeled by setting $\lambda_{ni} = 0$ for all $i \in \mathcal{N}^\star$.
- In order to model decay of temperature at the nodes (other than the sink), we introduce a *virtual ground*, which we also refer to as node 0 hereafter, with temperature $\theta_0 = \theta_0(t) = 0$ for all $t \geq 0$. The temperature of the ground is not affected by the nodes. Again, this constant temperature of the ground can be modeled by assuming $\lambda_{0i} = 0$ for all $i \in \mathcal{N}^\star$. We assume that all nodes in $\mathcal{N}^\star$ are in contact with the ground at all times except for when they are in contact with the sink. Since the temperature of the ground is fixed at zero, all nodes in $\mathcal{N}^\star$ lose heat to the ground in much the same way an object with a temperature higher than the ambient temperature loses energy (in the form of infrared radiation) to the surroundings. We assume that $\lambda_{i0} \ll \lambda_{ij},\ i, j \in \mathcal{N}$ so that the exchange of heat between two nodes $i, j \in \mathcal{N}$ takes place at a higher rate than the loss of heat to the ground.
- The rate of heat exchange is additive. In other words, when a node is in contact with more than one other node (in addition to the ground), the rate at which its temperature changes is the sum of the rates at which the temperature would change when it were in contact with each of these nodes separately as given by (2).

The heat exchange rules stated above can be summarized by the following differential equation that governs the evolution of temperature: For all $i \in \mathcal{N}^\star$,

$$\begin{aligned} &\frac{d}{dt}\theta_i(t) \\ &= \sum_{j=1}^{n} \lambda_{ij}(\theta_j(t) - \theta_i(t))\ \mathbb{1}\left\{||L_i(t) - L_j(t)||_2 \leq \gamma\right\} \quad (3) \\ &\quad -\mathbb{1}\left\{||L_i(t) - L_n(t)||_2 > \gamma\right\}\ \lambda_{i0}\ \theta_i(t)\ , \end{aligned}$$

where $\mathbb{1}\{A\}$ is the indicator function of event A, i.e.,

$$\mathbb{1}\{A\} = \begin{cases} 1 & \text{if event } A \text{ is true} \\ 0 & \text{otherwise} \end{cases} .$$

As mentioned earlier, we assume that the communication range γ is the same for all nodes for simplicity of exposition. However, our model can be easily modified to cover the case where the nodes have different communication ranges. Note that, since the trajectories of the nodes are (continuous-time) stochastic processes, so are the temperatures of the nodes. The input to this set of differential equations is the trajectories of the nodes, and the output is the temperature processes $\Theta_i, i \in \mathcal{N}^\star$, of the nodes. Finally, we assume that the initial conditions are given by $\theta_i(0) = 0$ for all $i \in \mathcal{N}^\star$.

With the assumed initial conditions, it is easy to verify that the following holds:

Proposition: *The temperature processes* $\Theta_i, i \in \mathcal{N}$, *produced by the differential equations in (3) are stable in the sense that, starting from any non-negative initial values* $\theta_i(0) < \infty$, $i \in \mathcal{N}^\star$, *the temperatures satisfy*

$$\theta_i(t) \leq \max\{T,\ \max\{\theta_i(0); i \in \mathcal{N}\}\} \quad \text{for all } t \geq 0 \text{ and for all } i \in \mathcal{N}\ .$$

Furthermore, if we assume the initial conditions $\theta_i(0) = 0$ *for all* $i \in \mathcal{N}^\star$, *we have* $0 \leq \theta_i(t) < T$ *for all* $t \geq 0$ *and for all* $i \in \mathcal{N}^\star$.

The temperatures governed by the differential equations in (3) have several other intuitive properties, which make our scheme suitable in practical settings. For example, suppose that there are two nodes that often stay in contact with each other for a long period. In this case, one should expect that, from the perspective of other nodes that meet with these two nodes, they should be (approximately) equally preferable as relay nodes. This is because these two nodes can exchange messages with each other regardless of which of the two nodes take on the messages in the first place. As a result, one expects the two nodes to have similar temperature profiles.

Another desirable property is that if a node stays in contact with the sink for a long time, its temperature will asymptotically approach that of the sink. Clearly, this is a natural property to expect; a node that spends much time in contact with the sink should be able to deliver messages to the sink on behalf of other nodes and, hence, be viewed as a good relay node by them. This is indicated by a high temperature of the node in our model.

These observations suggest a form of *weak transitive relation* exhibited by the temperature among the nodes. This is a key property exploited in a DTN setting where messages may need to be delivered through multi-hop routes. Furthermore, it provides similar temperature profiles to the nodes in the same group when group mobility is exercised, which permits automatic load balancing in our scheme.

Here we list a few conjectures regarding the asymptotic behavior of temperature processes and message delivery time.

Assumption 1: The trajectories $\mathbb{L} := \{\mathbb{L}_i; i \in \mathcal{N}\}$ of the nodes are ergodic and jointly stationary.

Assumption 1 implies that $\mathbb{C} = \{\mathbb{C}_{ij}; i, j \in \mathcal{N}\}$ is stationary and ergodic, where $\mathbb{C}_{ij}$ defined in (1) is the on-off process that indicates the one-hop connectivity between nodes i and j. [1]

Conjecture 1: *Under Assumption 1 and additional appropriate assumptions, the following distributional convergence holds:*

$$\Theta(t) := \{\theta_i(t); i \in \mathcal{N}\} \ \xrightarrow{D}\ \mathcal{F} \ \text{ as } t \to \infty$$

for some distribution function $\mathcal{F}$, where $\xrightarrow{D}$ denotes the convergence in distribution.

It is clear that, if the above distributional convergence takes place, the distribution function $\mathcal{F}$ is the steady state distribution of the joint temperature processes.

We say that $\mathbb{C}_{ij}$ is off at time t if $C_{ij}(t) = 0$. Let us denote the distribution of an off period in $\mathbb{C}_{ij}$ by $\mathcal{M}_{ij}$ for all $i, j \in \mathcal{N}, i \neq j$ and M_{ij} be a random variable with distribution function $\mathcal{M}_{ij}$. Note that the ergodicity assumption implies that, for every two nodes $i, j \in \mathcal{N}$ such that $\mathbb{P}[C_{ij}(0)] > 0$, the random variable M_{ij} is finite with probability one. For the following conjecture we assume that $\mathbb{E}[M_{ij}] < \infty$, i.e., the off period has a finite mean. Consider our proposed scheme under which, when two nodes meet, the node with a lower temperature transfers its messages to the other node.

Conjecture 2: *Suppose that $(\mathbb{L}, \Theta)$, where $\Theta = \{\Theta_i; i \in \mathcal{N}\}$, is ergodic and jointly stationary. Furthermore, assume $\mathbb{E}[\theta_i(0)] > 0$ for all $i \in \mathcal{N}$. Then, a message generated at any node will reach the sink in a finite amount of time with probability one under our proposed scheme.*

Note that the assumption $\mathbb{E}[\theta_i(0)] > 0$ for all $i \in \mathcal{N}$ implies that there is a multi-hop route to the sink for every node. Our second conjecture, if holds, will guarantee that the messages generated at any node will reach the sink in a finite amount of time with probability one under our proposed scheme. The intuition behind the second conjecture is as follows: Suppose that there is a node that cannot reach the sink in a finite amount of time, say node i. Then, the temperature of node i should decay exponentially to zero. In conjunction with the ergodicity assumption in place, this contradicts the assumption that $\mathbb{E}[\theta_i(0)] > 0$.

IV. Simulation Results

In this section we provide simulation results of our proposed scheme, which illustrate different properties of the temperature processes discussed in the previous section. We consider a simple five-node scenario in an one-dimensional network; node 5 is the sink, and the other four nodes (nodes 1 - 4) are located on the unit interval. The location of the sink is fixed at the center, i.e., $L_5(t) = 0.5$ for all $t \geq 0$. Node 4 is also fixed at location 0.9, i.e., $L_4(t) = 0.9$ for all $t \geq 0$. The remaining three nodes move according to the Random Waypoint (RWP) mobility model. The support or range of the mobility of nodes 1 through 3 is shown in Table I.

TABLE I

Support or range of mobility of nodes 1 through 3.

node	support
1	[0.0, 0.6]
2	[0.4, 0.75]
3	[0.6, 1.0]

Fig. 1 plots the location of nodes 1 through 4 at a finite set of sampling times. Under the RWP mobility model, when a node arrives at a waypoint, it (i) selects the next waypoint

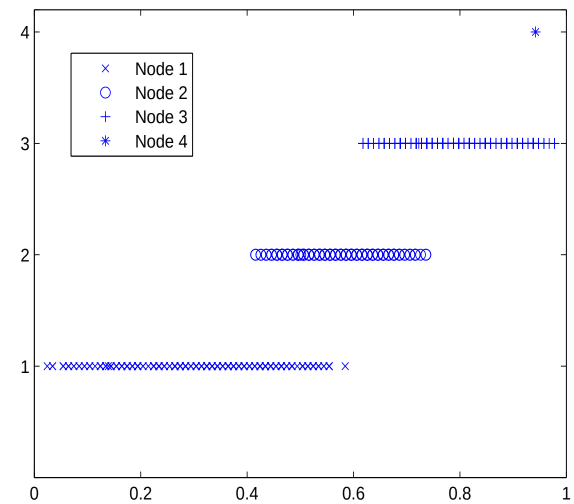

Fig. 1. Plot of locations of nodes 1 through 4 at sampled times.

according to the uniform distribution over its support and (ii) chooses a speed according to the uniform distribution over some compact interval $[s_{\min}, s_{\max}]$, where $s_{\min}$ and $s_{\max}$ denote the minimum and maximum speed, respectively. The node then moves towards the selected waypoint at the chosen speed. This process repeats when the node arrives at the next waypoint. In our simulation, $[s_{\min}, s_{\max}] = [0.001,\ 0.1]$. The minimum speed $s_{\min}$ in the RWP mobility model must be strictly positive [5,11]. Otherwise, the average speed of the nodes decreases with time to zero.

We set the communication range of the nodes to be $\gamma = 0.05$. With this communication range, nodes 1 and 2 are occasionally in contact with the sink. However, nodes 3 and 4 are never in contact with the sink. Hence, they cannot deliver messages directly to the sink. Node 3 must rely on either node 1 or 2 to relay its messages to the sink, whereas node 4 has to depend on node 3 to relay its messages.

For the virtual heat exchange, we assume (i) the heat exchange coefficient with the sink is $\lambda_{i5} = 0.05$, $i \leq i \leq 4$, (ii) the heat exchange coefficient among nodes 1 through 4 is $\lambda_{ij} = 0.01$, $1 \leq i, j \leq 4$, and (iii) the heat exchange coefficient with ground is $\lambda_{i0} = 0.002$, $1 \leq i \leq 4$. We set the temperature of the sink at $T = 100$.

The simulation is run for 5,000 seconds. In the simulation we approximate the continuous time system given by the differential equations in (3) using a discrete time system in which the state of the system is updated every 0.5 seconds. The resulting temperature profiles of the nodes are shown in Fig. 2. As shown in the figure, the nodes 1 and 2 have a higher average temperature than nodes 3 and 4. This is due to the fact that nodes 1 and 2 can come in contact with the sink, whereas the other two nodes cannot, resulting in a lower temperature. Moreover, it is clear from the figure that the

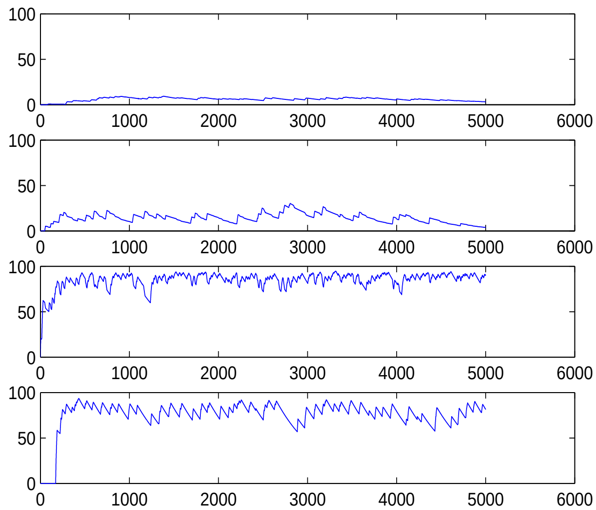

Fig. 2. Temperature profile of nodes 1 through 4.

temperature of node 4 is the lowest. This is a consequence of the fact that the temperature of node 4 can only increase when node 3 visits 4, transferring heat from itself to node 4. Therefore, this example demonstrates that the temperature used in our proposed scheme can successfully capture the nodes' heterogeneous mobility patterns, guiding the packet forwarding decisions at the nodes.

Recall that, under our scheme, when two nodes meet, the messages carried by the node with a lower temperature are forwarded to the other node with a higher temperature. As mentioned in Section II, we assume that the contact times (i.e., amounts of time two nodes stay in contact once they meet) are much larger than the amount of time required to exchange messages. Therefore, when two nodes meet, we assume that the exchange of messages occurs almost instantaneously. However, the effects of short contact times can be easily modeled as well.

We assume that messages arrive at each node according to a Poisson process with a rate 0.1/second and that each node has enough memory space to store messages without experiencing any message losses. We plot the evolution of queue sizes at nodes 1 through 4 in Fig. 3. The figure clearly shows that the queues at the nodes are stable (i.e., do not increase with time). Also, note that the queue size at node 3 tends to be larger than that of other nodes. This can be explained as follows: First, nodes 1 and 2 visit the sink regularly, giving them a chance to empty their queues by transferring their message directly to the sink. Secondly, node 4 has the lowest temperature and hence does not accept any messages from any other node. Thus, it only needs to store its own messages until the next visit by node 3 with a higher temperature. On the other hand, node 3, in addition to carrying its own messages, is required to accept all messages from node 4 during each visit to node 4. At the same time, since node 3 does not have direct access to the sink, it must store all the messages till it next encounters either node 1 or 2. Therefore, this leads to larger queue sizes at node 3.

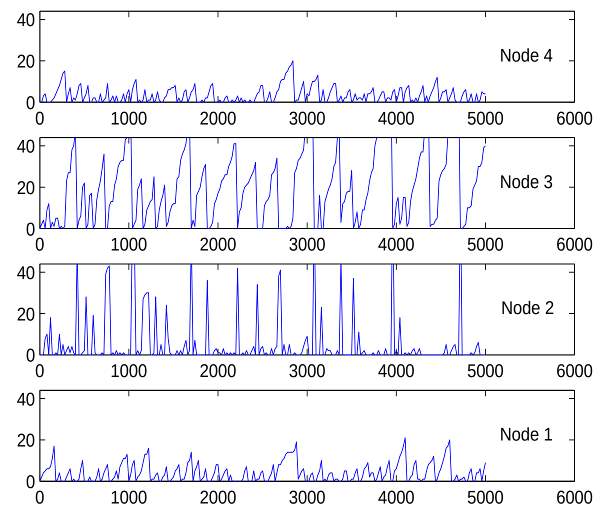

Fig. 3. Plot of queue sizes at nodes 1 through 4.

One important feature of our scheme based on the temperature is that it is completely distributed. The only overhead incurred by the scheme comes from exchange the current temperature of the nodes during each meeting. The exchange of their temperature allows them to update their own temperature according to the rule in (3). The simulation results demonstrate that the temperature can be used to guide packet forwarding decisions by exploiting the underlying mobility patterns of the nodes.

V. CONCLUSION

We presented a new framework for designing a packet forwarding scheme for DTNs. It draws an analogy from thermodynamics, in particular, the laws of physics that governs heat exchange between objects, in order to capture heterogeneous mobility patterns of nodes. We considered a scenario where the messages generated at the nodes must be forwarded to an information sink in the network.

We defined a variable called *temperature* as a measure that indicates the ability of a node to relay messages to the sink (either directly or indirectly). We showed that the behavior of the temperature at a node, which follows a simple rule, possesses several properties that are natural and intuitive and is also consistent with those one would expect from a measure that reflects the quality of a node as a relay node. Then, we proposed a new packet forwarding scheme that uses the temperature at two nodes that meet to determine which node gets to transfer messages to the other node. The proposed scheme is completely distributed and can exploit heterogeneous mobility patterns of the nodes.

We showed that, starting from any finite initial values, the temperature at the nodes remains bounded. Then, we stated a few conjectures; first, under a set of assumptions, the temperature at the nodes converges in distribution. Second, under our proposed scheme where messages are transferred from a node with a lower temperature to a node with a higher temperature, under a suitable ergodicity and stationarity assumption, if every node has a strictly positive average temperature, messages generated by the nodes reach the sink in a finite amount of time with probability one.

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