Modelling and analysis of a mobility-based information network

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***Abstract*—An intermittently-connected, cooperative communication network in which mobility is indispensable is studied though an analytical random-walk model, its possible implementation with present-day technology is explored, and applications are discussed. Some important questions are answered, and many more are posed.**

Extended Abstract

Mobility-based information networks

In the typical communication network, any pair of "nodes" can talk to each other at any time, either through a direct link, or with the help of intermediate nodes (relaying). However, permanent connectivity is not always practical or even possible. Fortunately, when the application is delay-tolerant, and (some of) the nodes are mobile, an "intermittently connected" network in which a terminal communicates only when it is near another terminal may be practical. In these networks, mobility is — far from an impairment or even a secondary assistant — an *indispensable* ingredient.

Examples and applications

Delay-tolerant, intermittently-connected networks can arise, in one manifestation or another, in many application areas. These include wildlife monitoring [1], [2], and livestock monitoring [3]. These networks may also support delay-tolerant communication among humans, such as electronic mail, short text/voice/multimedia messages, and short file exchanges (as in [4]), as well as asynchronous Internet service (India's Daknet [5]). The Daknet is reminiscent of the earlier "infostation" architecture [6], [7].

In [1] (TurtleNet), endangered turtles are fitted with solar-powered electronic equipment including a GPS receiver, some simple sensors and basic radio communication devices. As turtle radios get in range of each other, they exchange recorded location and sensor information. Eventually, the recorded data is uploaded to a central collection point, when a turtle gets sufficiently close to it. In [2] (ZebraNet), selected zebras are fitted with a collar that has sensors and radio devices. The scenario is very similar to that of [1], with a key difference: there is no centralised data collection; as researchers move through the forest, they radio-receive recorded data from nearby zebras.

In [4] (Student Net), students were provided personal digital assistants (PDA's) with wireless communication capabilities, which, for several weeks, logged pairwise contacts between participants. The study concluded that a delay-tolerant network based on human mobility is possible, that routes exist between almost all participants via some multi-hop path, and that only modest replication of packets is required.

Store-carry-forward relaying

A fundamental feature in these applications is store-carry-and-forward (SCF) relaying, which has similarities with, but is different from, "typical" relaying. In a 3-node typical relaying scenario, A sends a packet to B, and B (almost) immediately forwards it to C. The presumption is that while A is not close enough to C for direct communication, A is in range of B, which in turn is in range of C. Under SCF relaying, A sends a packet to B, B stores it in memory, carries and waits until mobility makes B and C fall in range of each other, and then B forwards it to C. That is, a terminal wishing to communicate with another may transfer the information to a third terminal that happens to be nearby, with the idea that this terminal stores the packet, carries it, and eventually forwards it to another nearby terminal (which may or may not be the packet's ultimate addressee).

In some architectures, special nodes are introduced with the specific purpose of aiding SCF relaying. For instance, in [8], "data mules" randomly move and collect data from low power sensors. In [9], relatively simple static devices ("throw boxes") are placed in strategic locations to allow a passing mobile node to leave information for other nodes, and/or to retrieve information left by others. In some scenarios, the role of the "mule" may be played by a "normal" vehicle (such as a taxi or bus [10]) that "incidentally" visits the area of interest with certain regularity.

UWB as an enabling technology

Recently, ultra-wide-band technology (UWB) has been approved for communication applications in important world regions. UWB produces noise-like signalling, enables transceivers of low cost and complexity, and can coexist over segments of the radio spectrum in use by other technologies [11]. Present regulations effectively make negligible

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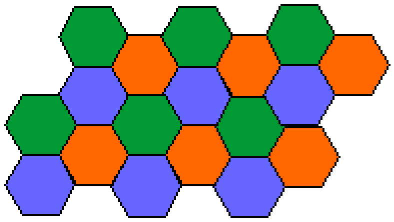

Figure 1. Small base-station-less "cells" for interference-control

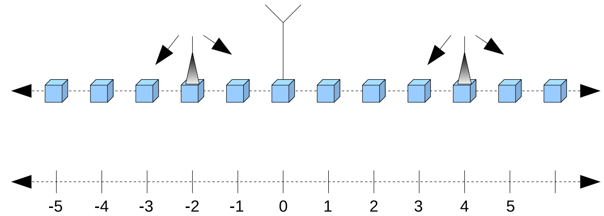

Figure 2. An idealised 1D mobility-based information network. The triangles denote mobile terminals, and the "Y" represents a fixed node (perhaps a data collection point, or a static relay-assisting node).

the effect of UWB devices on incumbent networks [12]. However, compliant UWB devices are severely range-limited, and hence suitable for a very limited class of applications (e.g., "cable-replacement", sensor networks, and location/tracking). Nevertheless, UWB could support communication applications among cooperative mobile terminals in some of the scenarios considered herein.

Capacity issues

The capacity of infrastructure-less wireless networks has attracted considerable attention recently. The seminal contribution, [13], attained a "pessimistic" result: in a fixed (static) wireless network, as the number of nodes, n, per unit area grows, the throughput per source-destination pair ("transport capacity") goes to zero as $1/\sqrt{n}$ (even under optimal scheduling and routing). However, [14] recognised that by exploiting "delay tolerance" and nodes' mobility, throughput per source-destination pair can be kept constant, as the number of nodes grows to infinity. The key intuition of [14] is that at any given time, there are many pairs of nodes such that both members of a pair are nearby, and hence enjoying a "good" channel. If all communication occurs between nearby nodes, less interference is produced, and higher throughput per pair is attained. In principle, each source could wait until its intended destination happens to be nearby to attempt information transfer, but such policy is too inefficient. Instead, a node should utilise one relay for it to deliver part of the information when it is near the destination[14].

A plausible network architecture

As shown in fig. 1, the area of interest may be divided into small "cells", and the available bandwidth allocated among these cells, as in a typical cellular network. However, there are no "base stations". Cells exist for interference control. A terminal needs location information, from which it determines the appropriate communication channel. Transmission power is determined by regulations. In order for information to travel from a cell to another, at least some terminals must be mobile, and perform relaying.

A tractable analytical model

The situations of interest can be idealised through a model in which random walkers hop from cell to cell in fig. 1, and exchange information when they "meet". Static "walkers" may exist to collect and/or help transfer information (as in [6], [9]).

We initially focus on fig. 2, the one-dimensional equivalent of fig. 1. Each terminal performs a "random walk" by jumping from its present location to the location that is to its right or to its left, with equal probability. When two terminals coincide in the same location, they can exchange information. This model may be appropriate when the roaming terminals do not adjust their mobility patterns in order to facilitate (or frustrate) communication, such as when sensor-carrying animals individually wander about a uniform area.

The low-density scenario: a critical question and its answer

A critical question is whether these networks are practical when the terminals are "few". In the random walk model, the extreme "low density" case is when there are only 2 walkers that need to exchange information periodically (perhaps sensor data), or even one single walker, that must periodically exchange data with a transceiver at a fixed location. A necessary condition for them to be able to transfer *all* the generated information is that they meet infinitely often, since information is generated at perpetuity.

Thus, the question can be rephrased as: Do two random walkers in a "large" (unlimited) area meet infinitely often (or do a given walker visit a given location infinitely often?).

It turns out that the answer depends on the dimensionality of the problem. If the walkers move over a one- or two-dimensional region, as in fig. 1 or fig. 2, they meet infinitely often with probability one. However, in a higher-dimension region, there is a positive probability that they never meet (possibly after a finite number of meetings)[15].

Many application scenarios can be reasonably approximated as two or even one dimensional (corridor, highway, etc). But the third dimension need not be spatial (for example it may be "spectrum" as in a frequency-hopping system), in which case the network would not work well, in a low-density scenario.

Information transfer limit for a pair

Of course, when terminals do meet, they do so for a limited time, and are subject to appropriate information-theoretic limits. If meeting duration is τ, and information transfer is upper-bounded by C bps, then at most τC bits/meeting can be transferred, in the 2-walker scenario. If p is the percent of the time that the pair spends in range of each other, $p\tau C$ is a reasonable measure of "capacity". With more than 2 terminals, relaying and broadcast scheme could increase capacity, but interference — or the measures taken to avoid it — would tend to reduce it.

Many interesting questions

Many important questions arise, even with as few as 3 "walkers" (terminals), and even if one is fixed. If A has information for B but meets C instead, how much (if any) of this information should be transferred to C for C to carry it and forward it to B (especially when there is some cost associated with relaying)? What is the system "relay gain", that is, the increase in capacity resulting from the use of relaying? If 3 terminals simultaneously meet, what criterion is appropriate to allocate the channel? In such case, is there a role for broadcasting, and which "gain" would result?

With an additional terminal, it becomes possible for two pairs to meet in adjacent cells, which brings up the issue of interference: which measures to take to mitigate its effects? A spatial frequency division scheme as in fig. 1 could be very inefficient when the terminal are "few"... when would such scheme make sense?

Conclusion

We have presented an idealised model of an intermittently-connected, cooperative communication network in which mobility is indispensable. Several specific applications and candidate enabling technology have been discussed. The model can be analytically formulated as a situation in which several "random walkers" exchange information when at least two meet, which leads to many important questions, and some answers.

Research involves several important stages including (i) identifying, motivating and conceptualising an interesting problem, (ii) building a model that is simple enough to be tractable but general enough to be useful, (iii) posing important relevant questions, and (iv) providing analytical or numerical answers to those questions. One can argue that the word "results" (or more generally "research output") should apply to all four of these items. In this sense, we have reported significant research output concerning items (i), (ii), and (iii). Concerning (iv), we admit to presently having many more questions than answers. Nevertheless, we are optimistic that we have contributed by disseminating some of the available outputs of our work.

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