Enabling adaptive traffic scheduling in asynchronous multihop wireless networks

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We present work-in-progress developing a communication framework that addresses the communication challenges of the decentralized multihop wireless environment. The main contribution is the combination of a fully distributed, asynchronous power save mechanism with adaptation of the timing patterns defined by the power save mechanism to improve the energy and bandwidth efficiency of communication in multihop wireless networks. The possibility of leveraging this strategy to provide more complex forms of traffic management is explored.

1 Introduction

This abstract describes work-in-progress developing a communication framework that is well attuned to the resource limitations and dynamic nature of the wireless multihop networking environment. The proposed approach is interesting because it is provides a completely localized, adaptive solution. In particular, there is no requirement for synchronization, clustering or shared control elements. These characteristics are especially important in the multihop wireless environment, which has the unique problem that disjoint flows – despite having no nodes in common – interfere with each other.

The framework is based on a simple CSMA underlayer and a lightweight power saving mechanism. The power saving protocol establishes local sleep-wake schedules that reduce nodes' energy consumption. These schedules also implicitly create high level transmission schedules defined by the intervals during which pairs of communicating nodes are both awake. We believe that the timing of these intervals can be manipulated to improve the efficiency of the CSMA access. Moreover, because the CSMA underlayer is ultimately responsible for ensuring appropriate channel access, it is possible to use techniques that are sometimes "imperfect" in their attempts to adapt to a dynamic environment.

More speculatively, we suggest that these techniques lead to the emergence of roughly periodic traffic patterns, making it easier to assess and predict link and region capacity. This may make it possible to provide higher layer resource management capabilities than are currently feasible in multihop wireless networks.

2 CSMA in multihop networks

Any simple CSMA protocol that is distributed and asynchronous can provide the lowest underlying communication layer for our framework. The work is currently based on IEEE 802.11 "demo ad hoc mode", but the communications interfaces found on nodes used in many sensor networks are similarly suitable.

CSMA MAC layers are generally proposed for decentralized wireless networks. The "sense and send" operation, often combined with RTS/CTS to mitigate the problems of hidden and exposed terminals, is distributed and asynchronous. Despite its flexibility and simplicity, CSMA is also relatively inefficient due to the time spent in defer, channel assessment and backoff states and failure to optimally schedule all feasible simultaneous transmissions.

3 Power save protocol

It is well-known that the energy consumption of a wireless network interface in the idle state is much higher than its energy consumption in a sleep state. However, it is only in the idle state that the interface is able to receive incoming frames. In the case of a network with an AP, the AP establishes a synchronous traffic schedule and buffers incoming traffic destined for sleeping nodes [1].

In a decentralized multihop wireless network, considerable overhead is required to maintain synchronization and dynamic clustering, especially in the case of resource-limited devices and dynamic networks subject to partition and merge. Therefore, the power save protocol we define is designed for asynchronous distributed operation. It is based on well-known quorum structures (see e.g. [1, 2, 3, 4])

*Contact: Laura Marie Feeney(`lmfeeney@sics.se`). This work was supported in part by the Ambient Networks project, which is supported in part by the European Commission under its Sixth Framework Program. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Ambient Networks project or the European Commission.

[1] A 'sleeping node' is a node whose network interface (not necessarily other system components) is in a sleep state .

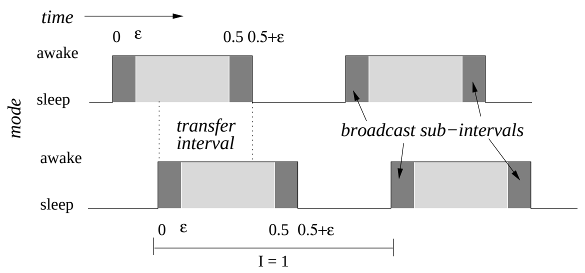

Figure 1: Overlap principle: At most two transmissions are needed to reach a neighbor.

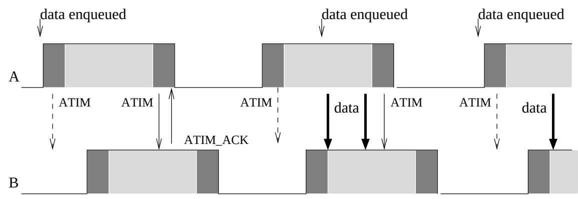

Figure 2: Traffic announcement: The transmitter sends an ATIM in each broadcast sub-interval. The receiver responds only if the estimate in the ATIM is bad.

to ensure that nodes are pair-wise able to determine times at which they are both awake.

Sleep-wake patterns All nodes follow a common sleep-wake pattern, with an unknown phase difference between each node pair. The pattern is defined such that small known *broadcast sub-intervals* for each node are guaranteed to overlap with the awake intervals of its neighbors.

Formally, given a common period I (normalized to 1) and a value $0 < \epsilon < 0.25$, let each node maintain an awake interval of length $.5+\epsilon$, followed by a sleep interval of length $.5 - \epsilon$. Either the first or the last sub-interval ϵ of each awake interval (the *broadcast sub-intervals*) will be fully contained in the awake interval of each neighbor, regardless of the phase difference between them.

See Figure 1 above and [3] for a proof and see [2] for a more general discussion of quorum based techniques in energy management for ad hoc networks. In particular, we note that more complex patterns can be used to obtain lower duty cycles and additional energy saving.

Traffic announcements A message transmitted during each of a node's broadcast sub-intervals is eventually received by all of its neighbors, providing an effective mechanism for transmitting broadcast messages.

A transmitter with pending unicast traffic also uses this mechanism to broadcast a traffic announcement (ATIM). The ATIM contains the transmitter's own interval clock and current estimate of its phase difference with respect to each intended receiver. Each receiver compares estimated phase difference in the ATIM with the phase difference it observes based on the time of packet arrival. If they differ, the receiver sends an ATIM-ACK, with updated phase information, to the transmitter. (Fig 2).

Data transfer The traffic announcement protocol allows each transmitter and receiver pair to discover the *transfer window* during which they are both awake. Given a set of pending messages and their transfer windows, the transmitter can then schedule the transmissions appropriately (e.g. constrained FIFO).

All transmissions use the underlying CSMA channel access (e.g. IEEE 802.11), which is also responsible for managing re-transmissions and other transmit parameters. While the framework does not preclude the use of cross-layer information in packet scheduling, discussion [5] of the pros and cons of cross-layer interaction suggests the potential value of maintaining this abstraction barrier.

Network operation The operation of the power save protocol can be transparent to the operation of other protocols. In particular, ad hoc neighbor discovery and routing protocols based on some combination of broadcast and unicast traffic to discover routes (e.g. RREQ and RREP) do not need to be aware of the broadcast sub-intervals or ATIM exchange.

Naturally, the reduced duty cycle has some performance impact, in that available transmit times are restricted. In the following section, we suggest that the impact is, in fact, likely to be minimal with respect to network capacity. The effect on route latency is likely to be more significant and study of proper tuning of ad hoc routing parameters is future work.

The effect on mobility management (e.g. route repair) is similar. The response to link failure detection is not altered, although the timing may be. This effect is due to possible loss of ATIM/ACK messages, as well as reduced opportunity for "snooping" (rarely a good idea in an energy constrained system!) due to the reduced duty cycle.

Feasibility Performance evaluation has focused on studying the impact of the power saving scheduling on the the overall capacity of the network. The simple Matlab-based probabilistic simulation results are intended primarily as a feasibility study.

The simulation scenario is based on a static network of uniformly distributed nodes, with fixed nominal transmission and interference ranges. The MAC layer is assumed to prevent transmissions within interference range of a sender or receiver, while transmissions within communication range always succeed without error. Flows are assumed to be uniform size, periodic transmissions between randomly selected source-destination pairs. All flows use fixed shortest path routing.

The network is filled to capacity by adding flows to

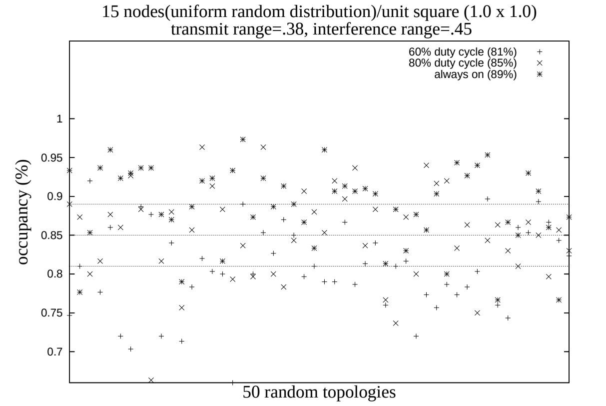

Figure 3: Channel occupancy: The proportion of usable transmission time obtained by a set of random source-destination pairs (50 random topologies and mean).

the network, until no more flows can be added. One key metric is then the proportion of time that the channel is occupied, which implies a "good" phase distribution. Figure 3 shows the channel utilizations that are obtained with different duty cycles in the network. Results are shown for each of fifty randomly generated topologies and source-destination pairs, for each of three values of $0.5 + \epsilon$ (0.6, 0.8, and 1.0).

The results suggest that there is a moderate decrease in channel occupancy (from 89% to 81%) as the duty cycle decreases from 100% to 60%, suggesting a fairly moderate performance impact from obtaining significant energy saving. Because the simulation does not take into account overhead associated with the MAC and power save protocol, it is not appropriate to conclude more than that the results suggest feasibility.

4 Traffic Management

The structure created by the power save mechanism is useful in two ways. It be used to improve the efficiency of the underlying CSMA and, by imposing a roughly periodic traffic patterns, we further speculate that it can be used to assist in capacity assessment and traffic management.

Despite this structure, the system nevertheless reflects the fluid, asynchronous behavior of the underlying framework, so that overlying mechanics cannot rely on fixed behavior. But because they are not ultimately responsible for arbitrating channel access, they are also free to use approximate or heuristic techniques and rely on the CSMA underlay for "backup".

4.1 Packet scheduling

In an multihop wireless network, only a small fraction of the nominal bandwidth is effectively available on a link[6]. Interference effects extend over multiple hops, leading to contention between disjoint flows, as well as self-interference along a flow. The former situation is especially challenging, because there is no common element that can arbitrate between flows.

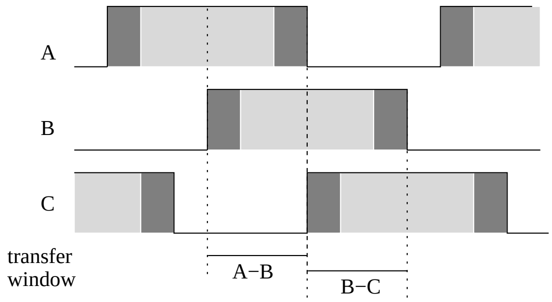

Figure 4: A "nice" phase distribution. In flow A-B-C, hops A-B and B-C cannot interfere with each other. No transmission is likely to defer because of the others.

CSMA protocols deal with contention by forcing nodes to backoff if they detect interference. This can be inefficient, especially when interferers are not in communication range and it is necessary to probe. If the transfer windows are distributed such that interfering transmissions are avoided and each transmitter detects a clear channel, the CSMA channel access becomes more efficient (i.e. less likely to require exponential backoff). Figure 4 shows a trivial example of a nice distribution of transfer windows.

Phase adjustment It is easy for a node to adjust its phase relative to its neighbors, by remaining awake for the union of the old and new schedules, while the relevant phase estimates are updated via the ATIM protocol. Although the phase adjustment is locally cheap, it affects the distribution of transfer windows not only at the adjusting node, but also at its neighbors. It is therefore difficult to determine, without non-local information, the impact of an adjustment.

Randomized adaptation It is hard to explicitly construct a "good" phase distribution in a distributed fashion: Some STDMA link assignment problems are known to be NP-hard. Phase adjustment also leaves open the problem of stability and the risk of creating a feedback loop, especially with multiple flows.

A randomized approach is for a node to adjust its schedule by a random amount in response to locally detected congestion. To avoid too frequent or competing adjustments, the decision to perform phase adjustment is also probabilistic, based on the time since the last observed adjustment.

This heuristic has the advantage of being simple, though randomization does not provide any guarantee of improved efficiency. With respect to stability, it provides a bound on the number and distribution of phase adjustments. This method seems to be effective only in relatively lightly loaded networks, where there is some improved configuration to be discovered.

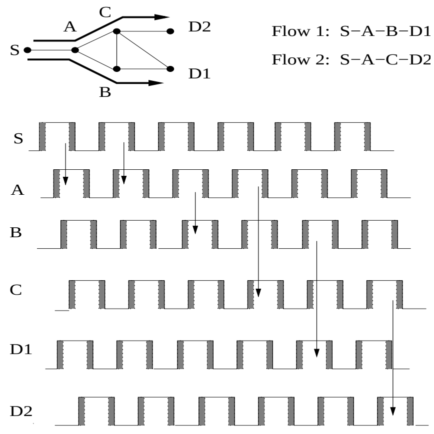

Figure 5: Multi-interval adapatation: Transmissions are distributed to avoid contention and self-interference. The network accommodates a load of one packet per flow in every six intervals without contention.

Multi-interval adaptation Because of the capacity limitations of ad hoc networks, especially due to self-interference along a flow, it is useful if adaptation can extend over several awake intervals. For example, if a transfer window proves congested because it overlaps with the transfer window used by an interfering node pair, it may not be possible to find a phase adjustment that resolves this state. It may be preferable for the transmitters to access the channel during alternate transfer windows, allowing the flows to adapt to a transmit rate better supported by the network. Figure 5 shows an example of a configuration in which transmissions are distributed across several intervals.

Periodicity Transfer windows are periodic, so there will be a tendency for transmission patterns to develop some periodicity as well. But because the offered load is not periodic and because transmissions take place anytime during the transfer window subject to unpredictable CSMA behavior, the result is only partially predictable behavior.

4.2 Capacity Assessment

The ability to provide even a crude link capacity estimate is useful in providing some higher level services. We expect that the framework will simplify this assessment, because the transfer window and super-frame structures identify a small set of intervals over which availability is considered. Two applications of such assessment are routing and admission control.

Routing The framework is agnostic with respect to ad hoc routing protocols. However, some reactive routing methods accumulate various route parameters during route discovery and the destination uses this information in selecting a route. Capacity metrics like those described above can easily be used to inform the route selection process. The problem of jointly creating a route and a phase distribution is much more challenging, however.

Admission control Given the decentralized structure and severe capacity constraints in the ad hoc environment, "soft" admission control is potentially important, less in a traditional QoS context than in ensuring a reasonable operating regime for the network. Capacity assessment is useful for such admission control. Given a route, each node can assess its transfer window with respect to the next hop node. If the transfer window (or super-frame) seems "too congested" to support the new flow, it can be deprecated.

5 Conclusion and Future Work

This abstract has outlined some elements that are being used to build an energy efficient MAC framework that combines the advantages of simple channel access support for simple traffic scheduling and eventually for advanced traffic management functionality.

Preliminary simulation results are moderately promising in suggesting that the proposed approach is feasible. There remains substantial future work in developing more detailed and realistic simulation of protocol performance, particularly with respect to details of the underlying CSMA MAC protocol and propagation environment. Many of the speculative ideas presented here provide exciting opportunities for future exploration.

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