Colorwave: A MAC for RFID Reader Networks

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***Abstract*— We present Colorwave, a medium access control (MAC) protocol designed for wireless sensor networks such as Radio Frequency Identification (RFID) reader networks. A network of readers will collaborate for a common application such as item-level monitoring in supply chain management. Readers may be deployed in an ad hoc manner, and readers must not interfere with one another's reader-to-tag communication. Colorwave capitalizes on the localized nature of reader-to-tag communications to provide an on-line, distributed, and localized MAC protocol that minimizes reader-to-reader interference.**

I. Introduction

Radio Frequency Identification (RFID) systems are a form of sensor networks that are used to identify physical objects. Instead of sensing environmental conditions such as temperature and humidity, an RFID system 'senses' the unique identifier and other information stored in Radio Frequency (RF) tags affixed to objects. RFID interrogators, or readers, perform this 'sensing' by actively transmitting a signal to communicate with the RF tags[6].

The RF tags are extremely low functionality devices that communicate with readers only and are unable to detect the communications from other tags. The tags do not actively send out a communication signal. Instead, they use either load modulation or backscatter communication (depending upon the communication signal frequency used) to communicate with the readers. Furthermore, the tags perform operations only under the direction of the readers.

The information obtained from the tags is transmitted from the readers to an application system, such as an inventory management system or a quality control application. The reader-application system communication typically uses a different medium than that used for reader-tag communication. Reader-reader communication may occur over any medium.

The use of a distinct communication medium for reader-tag communications results in localized wireless communications. The localized nature of these communications (readers are communicating with tags and not other readers) is distinct from the neighborhood nature of communications in ad hoc wireless networks (devices communicate with other devices and act as communication routers).

Many applications, such as real-time inventory detection and automated product receiving in supply chain management, require RFID readers to be able to read tags anywhere within a large geographic area. Due to the limited range inherent in the reader-to-tag communication, readers must be deployed in high densities over the entire area. Furthermore, the real-time requirements of the applications require the readers to attempt to 'sense' the tags as often as possible. The high reader density and the high communication rate necessitate the efficient access of the wireless reader-to-tag communication medium to minimize reader-reader interference, also called *collisions*.

High-density reader networks may not admit or permit a statically determined or centrally controlled coordination of the reader-to-tag communications due to factors such as governmental regulations and mobile readers. In addition, reader-to-tag communication uses the freely available Industrial-Scientific-Medical (ISM) frequency bands; therefore, the readers must be able to adapt to localized interference caused by non-reader devices. A distributed, localized medium access control (MAC) protocol applied by the readers for their reader-to-tag communications can be used to satisfy the governmental and system constraints as well as provide for adaptability to non-reader interference sources.

Colorwave is a simple, distributed, on-line MAC protocol for localized sensor networks such as RFID reader networks. The distributed nature of the protocol allows each reader to minimize collisions based upon local information. Interference with non-reader devices may also be adapted to. Global communication and information sharing are not required for Colorwave to operate efficiently. Thus, Colorwave enables the RFID system to easily adapt to local disturbances, such as the installation of a new RFID reader or the presence of a mobile RFID reader.

The remainder of this paper is organized as follows. Section II examines existing wireless MAC protocols and their applicability to RFID reader networks. Section III details the Colorwave algorithm. Section V presents our experimental results, and Section VI presents our conclusions.

II. Related Work

The medium access control problems encountered in RFID systems are similar to those encountered in random access and ad hoc networks. Wireless ad-hoc networks consist of independent devices that may communicate over a shared wireless medium only. The MAC problem for these networks is the problem of allocating communication times to devices such that communication performance is optimized. Many variants of the MAC problem for wireless ad-hoc networks have been studied, and many MAC algorithms have been proposed[3][8][5][10].

These algorithms have only limited applicability to the MAC problem encountered in RFID systems due to the different nature of the communications in the two MAC problems. Communication in a wireless ad hoc network is primarily between devices in the network. The communication routing functionality implemented by each device in the ad hoc network enables data to flow through the network as a series of communications. Thus, a communication initiated by one device in the network will directly cause a series of communications throughout parts of the ad hoc network, potentially affecting the entire network. Communication in an RFID reader network, in contrast, is between a reader and tags in its vicinity. Readers do not route communication between other readers; therefore, their communications with tags affect only neighboring readers. Consequently, the RFID MAC problem admits a localized solution concerned only with collision avoidance, while the MAC problem in wireless ad-hoc networks requires a solution concerned with communication between neighboring devices and collision avoidance where some collisions cannot be detected by the communicating device, only by the receivers of the communication.

Wireless and packet-radio MAC protocols[9] often attempt to ensure the reliable forwarding of packets over a network of peers (c.f. FAMA-NCS[7]). The use of distinct control channels and coordinated communication are two methods used to ensure this reliable forwarding. There is no such forwarding required in either RFID reader networks or Colorwave. Fully integrated medium access is not what we are working towards here; any given RFID reader in this problem only needs to access that part of the medium immediately adjacent to it. Colorwave uses limited reader-to-reader broadcast communication to assist the reader network in reaching a locally optimal communication schedule. The broadcast communication is very fault-tolerant, and as such we do not need to ensure that it reaches its destination (the immediate neighbors of the sending reader); so we do not. A gross but perhaps illustrative analogy can be shown between the TCP/IP and UDP/IP protocols and the various families of MAC protocols applicable to packet radio networks and RFID reader networks, respectively. MAC protocols designed for wireless ad hoc networks will yield lower reader-to-tag communication rates than will the use of a MAC protocol designed for the more localized RFID reader network.

Existing queueing theory[2] is applicable to this work for the purposes of finding theoretical optimum transmission rates and visualizing the algorithms under discussion. The Colorwave simulations presented in this paper resemble a G/D/m/1 queueing system, in that the output is certainly deterministic over m nodes; however, there is the chance of rejection of a packet before index $m+1$ that tries to enter the system, as any colliding packets are discarded.

DCS Subroutine 1 - Transmission:

- *If* transmission requested:
  - *If* (timeslot_ID % max_colors) == current_color
    - *then* transmit
    - *else* idle until (timeslot_ID % max_colors) == current_color

DCS Subroutine 2 - Collision:

- *If* attempted transmission but experienced collision:
  - current_color == random(max_colors)
  - broadcast kick stating new color

DCS Subroutine 3 - Kick resolution:

- *If* kick received stating current_color
  - randomly change to different color within max_colors

Fig. 1. DCS Pseudocode

III. Algorithmic Overview

This section details a pair of distributed algorithms called Distributed Color Selection (DCS) and Variable-Maximum Distributed Color Selection (VDCS), which we also call Colorwave. We model the reader network as an undirected graph. Vertices represent individual RFID readers, and edges represent collision constraints; if two readers connected with an edge transmit at the same time, they will collide. The goal of both algorithms is to color, with a distributed algorithm, a reader network such that each reader node has the smallest possible number of adjacent nodes with the same color. This approach allows easy reservation of timeslots; a color is a periodic reservation for collision-free transmission of data (i.e., reader-tag communication). Colorwave additionally attempts to optimize the graph to the smallest number of total colors required to achieve a particular percentage of successful transmissions. Both algorithms are tolerant to transient readers and uncontrollable noise sources. This provides the adaptability required when operating within an ISM frequency band, or if performing an application where readers need to be mobile.

A. Distributed Color Selection (DCS)

A reader with a queued request for transmission transmits only in its color timeslot. If the transmission collides with another reader, the transmission request is discarded. Furthermore, the reader randomly chooses a new color and reserves this color, causing all of its neighbors to select a new color; theoretically clearing the timeslot for the next time the reader needs to transmit. This switch and reservation action is referred to as a "kick."

The maximum colors variable (max_colors) is an input to the DCS algorithm, and does not change throughout the functioning of the algorithm. Each reader keeps track of what color it believes the current timeslot to be (timeslot_ID). The distributed nature of the algorithm does not require synchronization between timeslot_ID on different readers[1].

DCS is implemented with three separate subroutines detailed in Figure 1. The first subroutine manages transmissions. The second subroutine manages collisions and the reservation

[1]Synchronization of data framing, however, is required, and is detailed in Section III-C

of a new "color" or timeslot. The third subroutine manages kick resolution, or communication with other readers. Each reader must calculate for each kick received whether its current color is the color referenced by the kick.

This is a *greedy* algorithm; a node's chances of colliding immediately after experiencing a collision are minimized at the expense of its neighbors. The distributed nature of the algorithm, lacking a central control, does allow for probabilistically pessimal cases (two colliding nodes switch randomly onto the same color, for example). However, a greedy algorithm caters more to our needs than an altruistic algorithm, as we wish a communicating reader to communicate with its tags as soon after queueing the request as possible.

B. Colorwave: Variable-Maximum Distributed Color Selection (VDCS)

Colorwave builds upon the DCS algorithm; the additional subroutines for Colorwave are detailed in Figure 2. In DCS, the maximum colors variable (max_colors) is fixed. This inflexibility proves to be detrimental if there is a variable probability of transmission between nodes and times of day. Thus, Colorwave implements a mechanism for dynamically changing the maximum number of colors.

In Colorwave, each reader monitors the percentage of successful transmissions. Five inputs to the algorithm determine when a reader changes its local value of max_colors: Two "safe" percentages of successful transmission, one for increasing max_colors and one for decreasing max_colors; two "trigger" percentages, where a node will alter max_colors only if a neighboring reader is doing so as well; and MinTimeInColor, a stabilization period after a max_colors change during which a node will not alter its max_colors value.

When a reader executing Colorwave reaches a Safe percentage to change its own value for max_colors , it will send out a kick to all neighboring readers. For example (and to clarify), when the number of collision-free transmissions experienced by that node [locally] since the last change of the local value of max_colors *divided by* the total number of transmissions by that node since the last change of the local value of max_colors *is higher than* the DnSafe percentage of the overall network, the reader will send out a kick to all neighboring readers with a value of (max_colors - 1).

If the phenomenon that is causing it to exceed a Safe percentage is local to that reader, the other readers will not have passed their own Trigger percentages and will not respond. However, if the phenomenon causing the collision value to exceed a Safe threshold is widespread, neighboring readers will most likely have exceeded their own Trigger thresholds, and a "kick wave[2]" will ensue. As kicks spread from the initiating reader throughout the entire system, a large portion of the readers in a reader system may change their value of max_colors.

[2]Also referred to as a Colorwave.

Colorwave Subroutine 1 - Color Change
- *If* collision percentage is past SAFE threshold AND time spent in current max_color exceeds min_time threshold
  - Change max_color up or down one (depending on threshold exceeded).
  - Next iteration, initiate kick to new max_color.

Colorwave Subroutine 2 - Kick Resolution
- *If* kick received stating current_color
  - change to random color within max_colors OTHER THAN current_color
- *If* kick received stating change to new max_color AND collision percentage is past TRIGGER threshold AND time spent in current max_color exceeds min_time threshold
  - Change max_color to kicked value.
  - Next iteration, initiate kick to new max_color.

All DCS subroutines are also in use.

Fig. 2. Colorwave Pseudocode

C. Synchronization Issues

Each communications timeslot is divided into a long reader-tag communication period and a short reader-reader kick period. The separation of communications eliminates the possibility of reader collisions in the presence of kicks. Synchronization for this framing is achieved by an unspecified global setting, such as a high-powered synchronization signal or precision clocks onboard the RFID readers.

IV. Discussion of Theoretical Optimum

The existing MAC that has been used as the baseline for distributed systems such as the RFID reader network in this problem is the Aloha family[1] of algorithms. Slotted Aloha has a theoretical throughput/channel utilization of $1/e \approx 0.368$, and tree-splitting algorithms push this limit to 0.478[2][4]. TDM (time-domain multiplexing) algorithms have a theoretical optimum throughput of 1, and it is upon this field where we build Colorwave. We can see this optimum by statically coloring our reader network to ensure no possible collisions, and assuming that transmission requests arrive to the RFID reader nodes with sufficient frequency that every time a node's color is active, it transmits. Colorwave is competitive if it can approach these static colorings (thus surpassing M/M/m and G/M/m backoff algorithms).

In the high channel utilization environment within which RFID reader networks operate, any M/M/m or G/M/m queueing algorithms, due to the exponential transmission component, will be outperformed by a deterministic transmission queuing algorithm (G/D/m) which has stabilized. For example, in an Aloha system, the attempted transmission rate $G(n)$ is a function of the probabilities of new arrivals and of backlogged nodes,

$$G(n) = (m - n)q_a + nq_r. \tag{1}$$

In our simulations, q_a = 0, all newly arriving requests are considered backlogged, and n is equal to the Colorwave probability of transmission multiplied by the number of nodes

(n_{net}) in the reader network. Thus, equation 1 reduces to:

$$G(n) = (t\%)n_{net}q_r. \quad (2)$$

A detailed analysis of Aloha[2] tells us that given $G(n)$ we can find the probability of success for each transmission:

$$P_{succ} \approx G(n)e^{-G(n)}. \quad (3)$$

With this and a reasonable assumption on the value of q_r, we can compare Colorwave to Aloha-type G/M/m algorithms.

V. Results of Experimentation

A. Simulation setup of DCS and Colorwave

Simulations of DCS and Colorwave were performed on 5 separate 250 node graphs, labelled “Sparse”, “Moderate”, “Dense”, “Grid”, and “Hex”. Sparse, Moderate and Dense are randomly-generated graphs, whereas “Grid” and “Hex” detailed networks of readers in a square-grid formation and a hexagonal-mesh formation, respectively.

To test the Colorwave algorithm, we selected four sets of inputs for the color changing aspect of the algorithm, detailed in Table I.

TABLE I

Colorwave test inputs

Input label	UpTrig	UpSafe	DnTrig	DnSafe
Set 1	90	93	99	98
Set 2	92	94	99.5	99
Set 3	95	97	99.7	99.4
Set 4	97	98	99.7	99.4

Simulations of 100000 iterations were run on each of the five example graphs with transmission rates of 5%, 25%, 50%, 75%, and 100% and Colorwave MinTimeInColor parameters of 100, 500, and 1000, providing 60 simulations per example graph.

The Colorwave simulators were written in Perl 5 and run on various Linux 2.4 i686 machines.

B. Performance of Colorwave

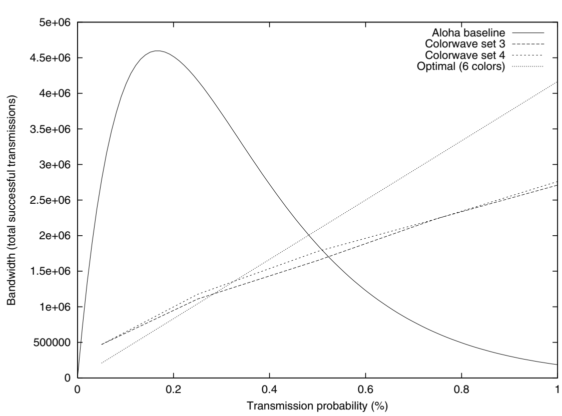

Fig. 3. Comparison of bandwidth achieved on grid graph

As stated above in Section IV, the experimental grid network can be optimally colored statically with 6 colors, whereas Colorwave produces results on average of 9 max_colors for a grid graph. Similarly, for the hex graph 9 colors are optimal and 13 max_colors is the average Colorwave result. Figure 3 shows the bandwidth achieved on our experimental grid graph using Colorwave sets 3 and 4 compared to the theoretical bandwidth achievable with a static 6-coloring of the grid graph and an Aloha solution with $q_r = \frac{1}{3}$. Higher values of q_r will start to produce non-trivial probabilities of high delay. Colorwave sets 3 and 4 show similar bandwidth and are competitive with the optimal coloring. Aloha outperforms Colorwave on a bursty medium, but in steady utilization approaching 1, Colorwave soundly defeats Aloha-like back-off algorithms. Colorwave performs slightly better in lightly loaded networks and slightly worse in heavily loaded networks than the optimal static solution

VI. Conclusions

We have presented Colorwave, a distributed, on-line MAC protocol for wireless sensor networks such as RFID reader networks. The simplicity of the Colorwave algorithm belies its superior performance, especially under high communication load. The reservation capabilities of Colorwave are essential to its performance under high communication load. The adaptability of Colorwave to any communication load ensures a high level of communication successes under all communication loads.

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