Cross-Layer Optimization for High Density Sensor Networks: Distributed Passive Routing Decisions

Primož Škraba[1], Hamid Aghajan[1], and Ahmad Bahai[1]

Stanford University, Stanford CA 94305, USA

Abstract. The resource limited nature of WSNs require that protocols implemented on these networks be energy-efficient, scalable and distributed. This paper presents an analysis of a novel combined routing and MAC protocol. The protocol achieves energy-efficiency by minimizing signaling overhead through state-less routing decisions that are made at the receiver rather than at the sender. The protocol depends on a source node advertising its location and the packet destination to its neighbors, which then contend to become the receiver by measuring their local optimality for the packet and map this into a *time-to-respond* value. More optimal nodes have smaller *time-to-respond* values and so respond before less optimal nodes.

Our analysis focuses on the physical layer requirements of the system and their effects of different system parameters on per hop delay and total energy used. Some examples of mappings are examined to obtain analytical results for delay and probability of collision.

1 Introduction

Wireless sensor networks (WSN) are a special case of ad-hoc wireless networks where the constraints on resources are especially tight. With a small power supply and limited processing power, any overhead equates to performance degradation. However, in any network system there is overhead in every layer of the network model. Therefore, improved performance may be achieved by reducing overhead through cross-layer optimization. This paper proposes Distributed Passive Routing Desicions (DPRD), a novel combined MAC/routing scheme based on geographic routing which achieves energy efficiency through minimization of control overhead. Reduction in overhead is achieved by utilizing implicitly distributed information of each node's location to make routing decisions at the receiver. Optimization and analysis of the protocol is done with physical layer constraints in mind. It is shown that with proper choice of design parameters, a low upper bound on delay can be achieved.

Communciation in WSNs is not between specific nodes, but rather based on some attribute that the nodes may possess. Perhaps the best example of this is where a user wishes to know what is being sensed in a particular area. In this case, it is irrelevant from which node the information comes from but only that the data quality and accuracy is sufficient. Also, the large number of nodes in the network makes tracking the network state impractical. For these two reasons, geographic routing is used in this protocol. To further reduce overhead to a minimum, the MAC layer is utilized to make the routing depend only on locally known information.

This paper begins by presenting relevant previous work. A description of the protocol and relevant parameters follows. Then the performance metrics are explained and the analysis is presented. Finally, resolving deadlocks in the protocol is discussed, followed by the conclusions and future work.

2 Related Work

There has been a lot of research already done on designing routing algorithms and MAC layer schemes specifically for WSNs. [1] showed that in a wireless environment, the unstable nature of the topology of a wireless network requires on-demand protocols. [2, 3] showed that routing with respect to remaining battery power can dramatically increase the lifetime of a network.

In addition to geographic routing, several other data-centric routing schemes have been proposed. [4, 5] describe variations of directed diffusion, which is based upon sink nodes advertising interest to sensing nodes to create gradients which packets can follow. Directed diffusion is designed for locally "pulling" information, since it uses a form of limited flooding. Geographic routing is more practical when data needs to be sent to or retrieved from a distant geographic area (i.e. querying the state of an area, notifying an information sink of an event). Greedy geographic routing was first proposed when GPS became available. It is the simplest algorithm and in most situations finds a near optimal path. The greedy algorithm was extended in [6], to include perimeter routing, thus allowing geographic routing to make its way around voids and to escape dead-end local maxima. Geographic routing, however, assumes that nodes are location aware[1].

In the MAC layer, the S-MAC protocol [7] deals with networks where nodes are on a low duty cycle and how to synchronize the sleep schedules without incurring too much overhead. The concept of a low duty cycle is key for WSNs, because they are intended to last over such long periods with small batteries.

Developed independently, two schemes have been proposed recently which embody the same idea as the protocol presented here. Geographic Random Forwarding (GeRaF) [8, 9], and Implicit Geographic Forwarding (IGF) [10], both propose receiver contention schemes. The main difference lies in how the receiver is chosen and in the stress of the analysis. The analysis of GeRaF stressed the energy savings achieved through sleep schedules most, while IGF is developed from a more algorithmic point of view, with a specific implementation proposed in the paper. The contribution of this paper is that the constraints of the physical layer are examined in the analysis as well as an analysis of the delay function.

[1] The cost of location awareness can be quite large and is a topic of research in its own right. However, in any sensing application of WSN's, it is crucial that each node have some spatial knowledge of its own location

3 Protocol Description

This protocol is based on geographic routing, which uses distributed information to achieve state-less operation, this work attempts to further utilize this distributed information to minimize overhead in the lower layers of the network, most notably in the MAC layer. The dynamic nature of the environment results in an unstable network topology. Thus, routes must be created in an on-demand fashion. As described above, given a destination location, geographic routing finds a route on a hop by hop basis, always routing towards the destination, thereby using locally optimum nodes to route a packet. However, in dense network, if local parameters other than node location (i.e. remaining battery power, link quality) are also taken into account, it quickly becomes impractical to exchange this information with all neighboring nodes. By using the broadcast nature of wireless communication and moving the routing decision to the receivers, this protocol allows this information to be incorporated without having to gather the data at the sending node.

The decision is made through "receiver contention." The sending node sends out a request to send a data packet (RTS). The packet includes its own location and the location of the final destination of the packet. Based on this information, each receiving node calculates its own optimality and maps this into a delay, τ. After this delay, the receiving node transmits a CTS packet to the sending node, unless another node has responded before it. Then the less optimal node does not transmit anything and turns off its radio to prevent overhearing.

This mapping from a measure of optimality to delay will be refered to as the "delay function." Consider some function $f(\theta) \rightarrow \tau$ where θ represents all relevant state information. To ensure that an optimal or near optimal node is selected, the delay function should map the state to delay in a monotonically decreasing fashion with respect to optimality (i.e. The more optimal the state of the node, the smaller the delay). To give good delay characteristics, $f(\theta)$ should be bounded. In real implementations, having a purely deterministic scheme without centralized control is impractical due to the possibility of deadlocks. However, the more random a protocol is, the larger the variance in performance will be. In a tightly constrained environment, worst case performance is more important than average performance, making protocols with a smaller amount of randomness more attractive. Before the performance of different delay functions can be investigated, a quantative metric of optimality must be found.

3.1 Optimality in Geographic Routing

The choice of a metric representing optimality depends on the goals of the system. To simplify the analysis, the smallest set of paramters is chosen. For any one hop using geographic routing, the location of source node, the location of the a candidate receiver node, and destination of the packet must be known. With a fixed transmission range, the optimal node is given as the neighbor of the source node that is closest to the destination of the packet as shown in Fig. (1.a). The metric of optimality is taken as the distance from a receiving node to the destination, D, normalized over the range $[L - R, L]$, where L is the distance from the source node to the destination and R is the transmission radius.

Given a specific topology, there is always a locally optimum next hop node. If a node knew that it is optimal, it should respond to the source node immediately. Since this would require knowing the full network state, a node must estimate the likelihood it is the optimal node. The likelihood is exactly equal to the probability that there are no nodes in the shaded area, as shown in Fig. (1.b)[2]. The area can be found as

$$A(L, R, r) = \int_{L-D}^{x'} \sqrt{D^2 - (x - L)^2} dx + \int_{x'}^{R} \sqrt{R^2 - x^2} dx \tag{1}$$

$$\text{where} \quad x' = \frac{L^2 - D^2 + R^2}{2L}$$

$$D = \sqrt{L^2 + r^2 - 2Lr\cos(\theta)}\ .$$

and ρ is the node density. A closed form expression for $A(L, R, r)$ can easily be found from 1. A two dimensional Poisson process is consistent with a "random" network and is used as the network model to find the probability of optimality. It results in a uniform distribution for a given number of nodes in a fixed area. For a Poisson process, the probability that there are no nodes in the shaded area in Fig. (1.b), is the probability of first arrival which can be written as

$$\mathbb{P}\{n_j \text{ is optimal}\} = e^{-\rho A(L,R,r)}\ . \tag{2}$$

Note that the probability is given by the network density and A. Implementing the complex calculation for A might not be feasible in a sensor node, but it is possible to approximate with a much simpler function of $\{L, R, D\}$. For the purposes of analysis, the assumption is that A or some estimate of A can be found.

4 Physical Layer

Several assumptions are made about the characteristics of the underlying physical layer. First, is the absence of power control. This is a fair assumption because the energy saving over short distances that are envisioned for a WSN (on the order of $\approx 10m$), would be negligible. Without this assumption, the optimality criterion is no longer valid and to minimize the total energy, the transmission energy must be jointly optimized with the number of hops. Any model of the number of hops has too much variance to be useful in the optimization, making this problem much more intractable. For the purposes of analysis, links are considered lossless. Link quality/probability of packet loss could easily be incorporated into the metric of optimality but is not considered here due to space constraints.

[2] The assumption of the circular transmission area is an idealization. A probabilistic transmission area would not change the analysis significantly.

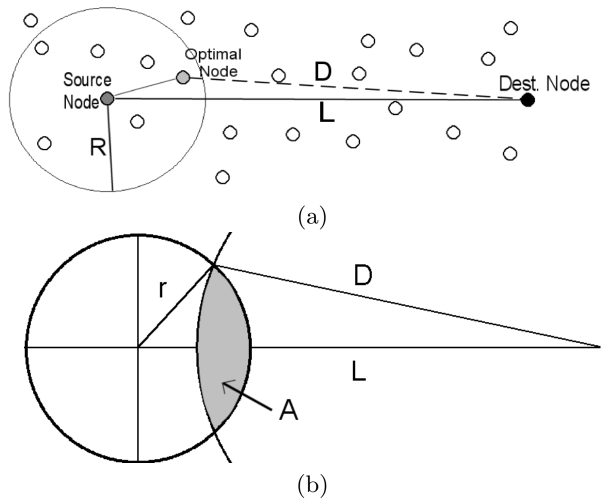


Fig. 1. (a) Example of the one-hop optimal node in a network, the node transmission range is R. (b) Geometric interpretation of receiver position in geographic routing.

DPRD is a CSMA/CA based scheme, and so the hardware must be available to do a carrier sense. The first consideration is the time it takes to perform the carrier sense, which will be referred to as δ_{CS}[3]. The longer the carrier sense is done, the smaller the probability of a miss or false alarm. However, a long δ_{CS} introduces several constraints on the system which are detrimental to performance.

Another important consideration in designing this protocol is that all the nodes that can hear the source node cannot hear the receiver node. To solve the resulting hidden terminal problem, [8, 9] introduced a dual-tone system. The solution this paper suggests is more flexible in terms of trading off performance characteristics. Two thresholds are introduced for the carrier sense SNR, γ_{CS} for carrier sense and $\gamma_{RECEIVE}$ for data transmission. If we assume a simple path loss model

$$P_R = P_T K \left[\frac{d_0}{R}\right]^{\alpha}$$

$$\mathrm{SNR} = \frac{P_R}{N_0} \geq \gamma$$

$$R \leq d_0 \sqrt[\alpha]{\frac{P_T K}{N_0 \gamma}} \; .$$

[3] Most previous work assumes the carrier sense to be instantaneous

Then the ratio R_{CS} and $R_{RECEIVE}$ becomes

$$\frac{R_{CS}}{R_{RECEIVE}} = \sqrt[\alpha]{\frac{\gamma_{RECEIVE}}{\gamma_{CS}}} \ . \tag{3}$$

The ratio should take a value between 1 and 2. 1 corresponds to a successful carrier sense being equivalent to a successful reception, while 2 is the most energy efficient value, since it ensures that no interferers can be present within 2R. While this does reduce the network capacity, generally WSN are used in low data rate applications and so the traffic is assumed to be light. It will be assumed from this point on that the value is near 2 and so the only collisions that occur are a result of two nodes responding to the RTS at the same time. This is the most conservative configuration in terms of energy usage. Thus for nodes neighboring the source node but out of receiving range, it is assumed they would be able to sense the original RTS and so shut down to avoid overhearing.

The introduction of duty cycles can be dealt with by simply stating that the network density is simply the density of the currently awake nodes. Thus if the true node density is λ, then $\rho = \lambda p$, where p is the probability of a node being awake. However, in this case a dual-tone system should be used to avoid a node waking up and transmitting. Alternatively, this analysis assumes the source wakes up all of its neighbors for a short period of time with an out of band wake-up scheme. Both methods have their advantages and disadvantages, but a quantative comparison is beyond the scope of this paper and does not affect its results.

5 Framework

The general framework for analysis studies the performance of the protocol with several "types" of delay functions, given certain physical layer parameters. First an analysis of energy efficiency is given, followed by a formulation to find the probability of collision and finally average one-hop delay. It will be shown that the latter two are the most crucial parameters affecting energy efficiency.

5.1 Energy Efficiency

A node in a WSN consumes energy in communication transmitting, receiving and listening. The energy spent in these activities is denoted E_T, E_R, and E_L respectively. It has been found in [11] that when communicating over a short range, the energy spent in receiving data is of the same magnitude as at the transmitter and the energy expended in listening often dominates the total energy consumed by a radio.

Thus, to send a packet from a source with N neighbors to a receiver, assuming no collisions occur, the total energy expended (assuming no overhead with reporting each nodes routing information) will be

$$E_{packet} = (N+1)E_{RTS} + 2E_{CTS} + 2E_{DATA} + E_L \ . \tag{4}$$

While the RTS packet will be longer in DPRD, the CTS will be shorter than each packet containing the neighboring nodes' local information, and so there will be significant reduction in control overhead. It is assumed that the energy used to transmit the actual packet is fixed as a physical layer parameter (i.e. Energy/bit, Number of bits/Packet). So all that remains is to minimize is the energy consumed in listening.

Using this protocol, it can be shown that once the RTS is sent, the neighboring nodes must listen for $\delta_{CS} + \delta_{PROC}$ before they transmit. δ_{PROC} represents the processing delay of the sending node. If a node is optimal, there will be no other node tranmitting before it, so no listening time is required. Assuming a node is not optimal it must detect either the optimal node's CTS or the actual data transfer. As shown in Fig. (2.a), since its delay, τ_1, will be greater than the optimal node's delay, τ_0, the only way to miss the "optimal" node is if τ_1 falls between the optimal CTS and the data transfer. This is exactly $\delta_{CS} + \delta_{PROC}$. This represents an upper bound on the receiving nodes listening time. Since no node knows a priori whether it is optimal, it must always listen before transmitting. Once a node has detected that it is not optimal, it would turn its radio off for the duration of the transmission to prevent overhearing.

The listening time of the source node is from the RTS until the optimal node responds. This is exactly the expected value of the delay function. So the expected amount of energy

$$\overline{E_L} = \left(\overline{f(\theta)} + N(\delta_{PROC} + \delta_{CS})\right) P_L \tag{5}$$

where P_L is the power consumed in listening mode. The formulation above assumes that the transmission is successful. Once collisions or lost packets due to channel conditions are considered, the formulation changes to

$$\overline{E_{total}} = P_S E_{packet} \sum_{n=0}^{\infty} n P_F^n \approx \frac{1}{P_S} E_{packet} \tag{6}$$

where P_S is the probability of success and P_F is the probability of failure. It is assumed that the physical layer is relatively robust and so the only failures coincide with collisions. So it can be seen that to reduce energy consumption, probability of collision and per hop delay must be reduced.

5.2 Probability of Collision

The probability of a node being chosen is given in 2 and is solely a function of A and node density (which is considered known). Hence, it is natural to make the delay function a function of A. This is becuase A encapsulates all relevant spatial information about the probability of a node being optimal. As stated in Sect. 3.1, the A is considered to be known, or more precisely, each node is able to calculate or estimate it upon receiving the information from the source nodes RTS packet. Note that only considering the spatial information is a special case of the formulation and more local parameters may be added as required.

The problem can the be stated as, what is the probability of collision given a delay function. The only source of collisions that will be considered will be when the CTS' from two receiving nodes collide. As discussed in Sect. 4, the carrier sense threshold is set so that not only can all relevant nodes hear the first CTS,

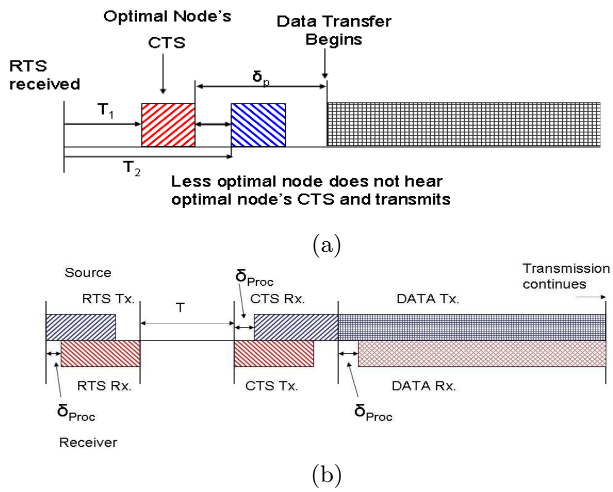


Fig. 2. (a) Example of how a node must listen for the turnaround time of the source node to ensure that it does not miss the optimal node's CTS (b) Example of successful RTS-CTS-DATA transmission. T is τ and δ_{Proc} is the processing delay.

but also assume that all neighboring nodes outside the range of the source node do not transmit, because they would sense either the RTS, CTS, or the data transmission.

To find the probability of collision note that $f(A) : A \to \tau$, where τ represents the delay from the end of the processing of the RTS as shown in Fig. (2.b). A collision will occur if two nodes calculate τs that are separated by less than $\delta_{CS} + \tau_{PROP}$, wher δ_{CS} represents the time required for a carrier sense and τ_{PROP} represents propogation delay. Based on this, we can find the following condition to ensure that no collsions occur.

$$\tau_i + \delta_{CS} + \tau_{PROP} < \tau_j \tag{7}$$

where τ_i represents the optimal node and τ_j represents the next closest node. In 7, τ_{PROP} is negligible due to the short range of the transmission links.

δ_{CS} is a parameter determined by the physical layer. The longer the carrier sense is done the smaller the probability of miss and probability of false alarm will be. However, the shorter it is, the smaller the probability of collision. Optimizing this depends on the hardware available and is beyond the scope of this paper. The effects of different δ_{CS} will however be explored. Taking a general function

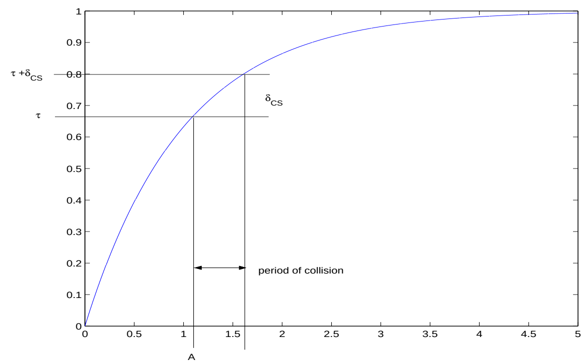


Fig. 3. Mapping from vulnerable period of collision to spatial separation in terms of A with respect to some general function $f(A)$, here shown as a concave function

that fulfills the criteria stated above, we wish to obtain an expression for a collision in terms of A rather than in terms of time. As shown in Fig. (3), for a given A and δ_{CS}, the interval in terms of A is given by

$$g(A, \delta_{CS}) = f^{-1}(f(A) + \delta_{CS}) - A \ . \tag{8}$$

By the independent increment property of the Poisson process, the probability of a collision is given by

$$\mathbb{P}\{\text{coll.}|A\} = 1 - e^{-\rho g(A,\delta_{CS})} = 1 - \frac{e^{-\rho f^{-1}(f(A)+\delta_{CS})}}{e^{-\rho A}} \ . \tag{9}$$

5.3 One-Hop Delay

Before investigating the performance of some test functions, the delay characteristics with respect to protocol parameters and energy effciency are presented. The delay characteristics are characterized as

$$\tau_{TOTAL\ DELAY} = \#\text{ of hops} \cdot E[\text{One Hop Delay}] \ . \tag{10}$$

The number of hops can be found to be roughly linear with distance and the variance decreases with node density. Since the actual number of hops that will result are more a function of the specific scenario topology, it is not considered a descriptive statistic of network performance. As long as the number of hops taken by geographic routing with perfect next hop knowledge versus the proposed algorithm is equal, it can be considered near optimal.

The expected value of one hop delay can be found simply by finding $E[\tau]$ which is equivalent to finding the expected value of the delay function.

$$E[f(A)] = \int_0^{A_{MAX}} f(A) e^{-\rho A} dA \ . \tag{11}$$

where $A_{MAX} \approx \frac{\pi R^2}{2}$. Thus the total delay is

$$\tau_{TOTAL\ DELAY} = \quad N_{hops}\left(\int_0^{\frac{\pi R^2}{2}} f(A)e^{-\rho A}dA + \tau_{DATA}\right) . \tag{12}$$

6 Delay Functions

Two classes of delay functions are examined, exponential and linear. The exponential was chosen becuase it best matches the model of the distribution of nodes and the linear model for its simplicity. For any delay function

$$f(A) : [0, A_{MAX}] \to [0, T_{MAX}] . \tag{13}$$

T_{MAX} represents the upper bound on one contention period, after which the source can know that either no nodes exist that are closer than the source or that a collision has occured (but for the purposes of this paper, it is assumed that a collision would be detected).

6.1 Exponential

For mathematical simplicity, a general exponential was chosen. To ensure that it is increasing and bounded it must be of the form

$$f_1(A) = \frac{T_{MAX}\left(1 - e^{-sA}\right)}{1 - e^{-s\frac{\pi}{2}}} . \tag{14}$$

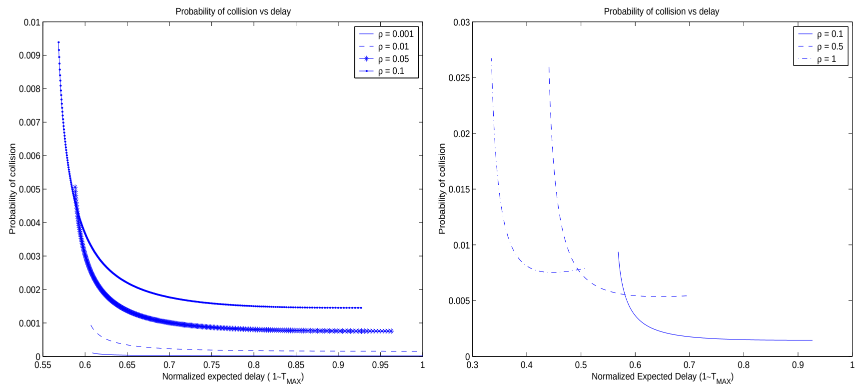
Using this we can find the one hop delay

$$E[f_1(A)] = \int_0^{\frac{\pi R^2}{2}} f_1(A)e^{-\rho A}dA = T_{MAX}\left(\frac{s\frac{1-e^{-\rho\frac{\pi R^2}{2}}}{1-e^{-s\frac{\pi R^2}{2}}} - \rho e^{-\rho\frac{\pi R^2}{2}}}{\rho(\rho + s)}\right) . \tag{15}$$

Trivially, 15 has a minimum at $s = 0$. This is because s must take a positive value (so that the resulting delay is positive). There is a tradeoff between delay and probability of collision, which is computed next. In this analysis, we use C which constitutes the delay over which we wish to study the probability of collision. So in all cases presented here, it can be assumed that $C = \delta_{CS}$.

$$\left(1 - e^{-sA}\right) \Rightarrow \frac{\tau(1 - e^{-s\frac{\pi R^2}{2}})}{T_{MAX}} \tag{16}$$

$$\Rightarrow f^{-1}(\tau) = \frac{1}{s}\ln\left(\frac{T_{MAX}}{T_{MAX} - \tau(1 - e^{-s\frac{\pi R^2}{2}})}\right) . \tag{17}$$



(a) (b)

Fig. 4. $\mathbb{P}\{\text{coll.}\}$ vs. Delay for (a) low node densities and (b) higher node densities

Equation 16 is the prototype function with a normalized range between $[0, T_{MAX}]$, while 17 is its inverse function. Substituting 16 and 17 into 9 and integrating over all possible values of A, the probability of collision is given by

$$\mathbb{P}\{\text{coll.}\} = \frac{1 - e^{\frac{\pi\rho R^2}{2}}}{\rho} - \int_0^{\frac{\pi R^2}{2}} \left(e^{-sA} - \frac{C}{T_{MAX}}(1 - e^{-s\frac{\pi R^2}{2}}) \right)^{\frac{\rho}{s}} dA \ . \quad (18)$$

in terms of s and C. As Figs. (4.a), (4.b), and (5.a) show, by changing the parameter s, increased delay can traded off to lower the probability of collision. The graphs show the operating curves of the protocol using an expontential delay function under different node densities. Figure (4.a) shows that At the low densities, an increase in density only marginally improves delay. In Fig. (4.b), the improvement in expected delay becomes more dramatic as the density increases. Figure (5.a) shows that at extremely high densities, it is possible to minimize both delay and probability of collision, due to the large probability that a "very" optimal node exists. From the graphs, it can be seen that the performance of the protocol improves with density, provided that C is small enough. As Fig. (5.b) shows, at high densities the probability of collision increases quickly with C.

6.2 Linear

For linear functions, there is only one possible form of the delay function

$$f_2(A) = \frac{T_{MAX}}{A_{MAX}} A \approx \frac{2T_{MAX}}{\pi R^2} A \quad (19)$$

$$f_2^{-1}(\tau) = \frac{A_{MAX}}{T_{MAX}} \tau \ . \quad (20)$$

The analysis for this function is straight forward. The delay is given by

$$E[f_2(A)] = \int_0^{\frac{\pi R^2}{2}} f_2(A) e^{-\rho A} dA = \frac{T_{MAX}}{\pi R^2} \left(\frac{2 - e^{-\rho \frac{\pi R^2}{2}} (2 + \pi R^2 \rho)}{\rho^2} \right) . \quad (21)$$

The probability of collision can be found in the same way as for the expontial function. First $f(A)$ (19) and its inverse function (20) are found. They are then substituted into 9 to give $\mathbb{P}\{\text{coll.}|A\}$. This is integrated over all A to find that the probability of collision is given by

$$\mathbb{P}\{\text{coll.}\} = \left(1 - e^{-\rho \frac{\pi R^2}{2} \frac{C}{T_{MAX}}}\right) \left(\frac{1 - e^{\frac{\pi \rho R^2}{2}}}{\rho} \right) . \quad (22)$$

For a linear system, it can be seen that the probability of collision increases with the node density and C, while the expected delay decreases with node density. Since there is no free parameter, the effect of the different ratios of C and T_{MAX} at different node densities can be seen in Figs. (5.c) and (5.d). Fig. (5.e) especially shows that for increasing values of C/T_{MAX}, the probability of collision can increase rapidly with node density to unacceptably high levels. Fig. (5.f) shows how the expected delay deceases as the node density increases. Fig. (5.g) shows the operating curves using the linear delay function at different node densities. It is interesting because it shows that for a fixed collsion window C, by choosing an optimal T_{MAX}, the protocol performs better in low node densities. This result does not consider that the lower density implies a larger probability of a void, which results in a breakdown of greedy geographic routing. This implies longer delays and higher energy usage. It is an open problem to find the optimal density that maximizes the probability that another node is closer to the destination but minimizes the probability of collision.

7 Resolving Deadlocks

The protocol as described is deterministic. If a collision does occur, it will occur every time a packet will have the same destination. This implies that a deadlock can exist between two nodes. A random term can be added to the delay function. Specifically, this term should take on some value $\pm k\delta_{CS}$ for $k = 0, 1, 2 \ldots$. Since deadlocks will be relatively rare and ideally δ_{CS} will be small, a value of $k_{MAX} = 2$ should suffice to resolve most deadlocks. In addition, as more local parameters are added, especially remaining battery power, more randomness will inherently be added to the system which will help prevent deadlocks.

8 Conclusion & Further Work

This paper has presented an analysis novel combined routing/MAC scheme. It was shown that physical layer parameters introduce limits on network parameters such as δ_{CS} on T_{MAX}. The purpose of this paper is more to highlight that given system parameters such as network density and physical layer constraints must be considered in designing an efficient protocol. The analysis of only two delay functions was presented, but it illustrates that in high node densities a more complex function performs better. This is especially important for geographic routing becuase it performs best in high node densities.

Much further research remains be done on how to add local parameters, such as battery power, to the delay function without altering basic system behaviour. Furthermore, since network node density is not uniform over space or time (e.g. lower densities due to node death), this protocol allows for the possibility of using an estimate of local node density to obtain optimal operating efficiency. While many questions remain open, the protocol has many of the desirable properties of deterministic MAC schemes while minimizing the control overhead of making routing decisions.

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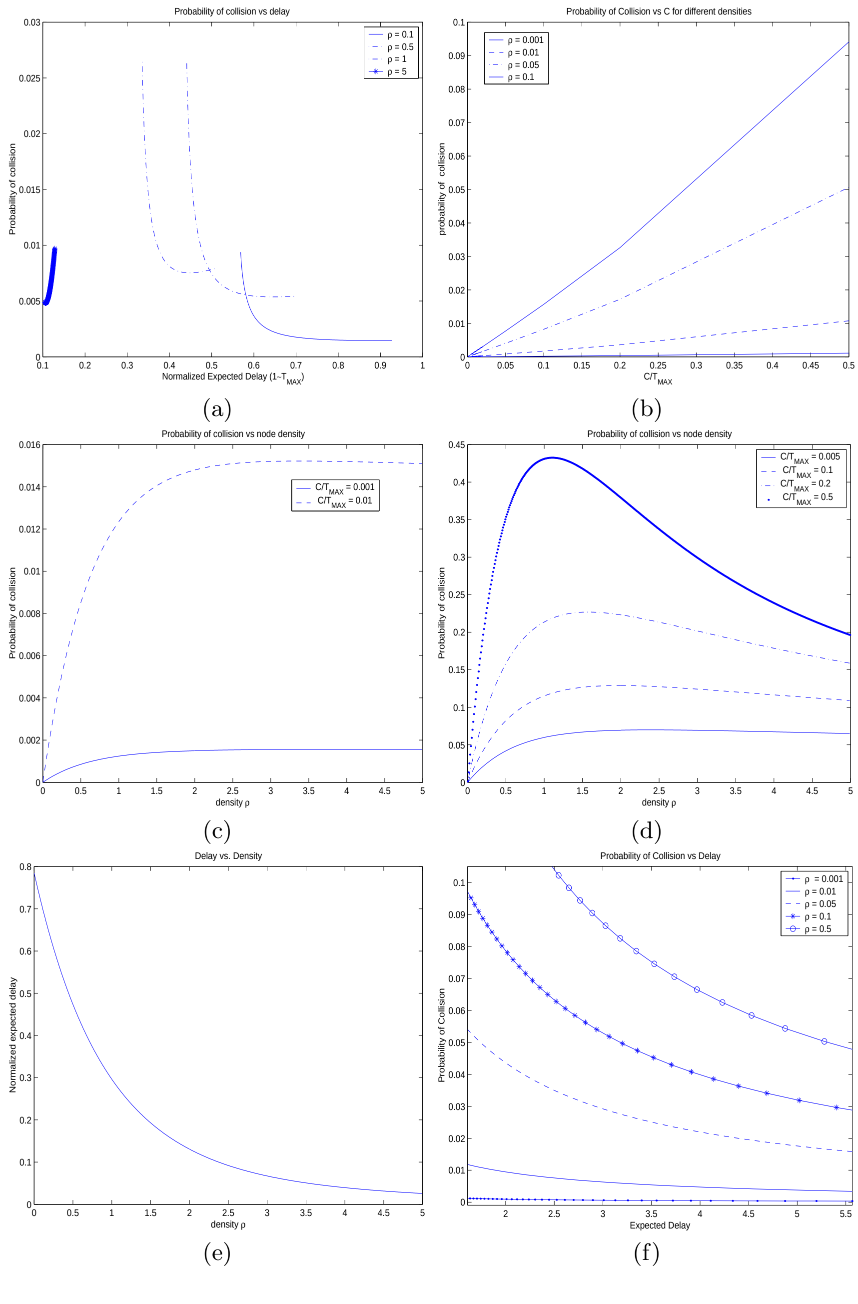

Fig. 5. (a) $\mathbb{P}\{\text{coll.}\}$ vs. Delay for highest node densities (b) $\mathbb{P}\{\text{coll.}\}$ vs. $\frac{C}{T_{MAX}}$ for a few node densities (c) $\mathbb{P}\{\text{coll.}\}$ vs. node density for $C \ll T_{MAX}$ (d) $\mathbb{P}\{\text{coll.}\}$ vs. node density for $C < T_{MAX}$ (e) Delay vs. node density for a linear delay function (f) $\mathbb{P}\{\text{coll.}\}$ vs. Delay for a node densities, varying T_{MAX} assuming $C = 1$