Geographic Transmission with Optimized Relaying (GATOR) for the Uplink in Mesh Networks

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Abstract

We consider communication in the uplink of a wireless mesh or sensor network. A group of mobile radios or sensors, hereafter called "nodes", have information to transmit to one or more access points (APs) (typically called "sinks" in sensor networks). When the channels from the nodes to the APs suffer from fading, then direct transmissions to the APs may have a high probability of failure, and packets may need to be relayed through other nodes. Under the conventional approach of routing, in which the relaying node is pre-selected, fading may also cause a high probability of failure at the router. Geographic approaches have been proposed that can improve performance by using opportunistic reception, in which a relay is selected from those nodes that can receive the packet correctly and move it toward the AP. Existing geographic transmission schemes use an ad hoc design for the protocol that selects the relay node. In this paper, we propose Geographic Transmission with Optimized Relaying (GATOR), which provides a mathematical design for relay selection in a time-slotted geographic communication scheme. The results show that GATOR provides better performance than direct transmission, routing, and other geographic transmission schemes, especially when the signal-to-noise ratios are low and APs are sparse.

I. Introduction

Wireless mesh and sensor networks present challenging problems in the design of network protocols. The reason is that the fading rate of the radio channels is usually higher than the rate at which network state information is exchanged among radios. Thus, conventional protocols that are based on pre-determined links and routes experience high rates of packet failure due

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to outage. In addition, for networks with more than a few tens of nodes, the network topology may change at a faster rate than the routing information can be propagated through the network. Again, conventional proactive and reactive routing protocols will often have severe problems because the routing information changes faster than new routing information can be distributed through the network. The difficulties in protocol design are further enhanced if the nodes also use random sleeping protocols to conserve energy. Thus, in the uplink of wireless mesh and sensor networks, the performance is often limited by fading channels and sleeping nodes, both of which result in packet failures.

Geographic transmission schemes can overcome these problems by taking advantage of opportunistic reception (OpRx), in which a sender broadcasts a packet to multiple receivers and a forwarding agent is selected from those receivers that correctly recover the message [1]–[9]. One of the first OpRx schemes described in the literature is alternate routing [10, Sec. IV.D], in which a packet that experiences too many transmission failures to the node selected by the routing table may then be forwarded by an alternate node. A similar scheme called selection diversity forwarding (SDF) is proposed in [1] and [11]. In SDF, an acceptable list of forwarding agents is pre-determined using channel state information fed back from neighboring nodes. Opportunistic multi-hop routing (ExOR), proposed in [8], is similar, with candidate forwarders chosen based on closeness to the destination. A stochastic forwarding approach is suggested in [9], where a forwarder is randomly chosen from a list according to an optimal distribution.

Taken to their extreme, the use of pre-determined routes is eliminated, and *geographic routing* [2]–[4], [12]–[16] can be used, in which packets are forwarded in the "direction" of the destination. Most work on geographic routing has focused on allowing routing in highly dynamic networks and on reducing the routing overhead (for instance, table updates or flooded route request packets). A geographic approach that provides diversity with respect to random sleep schedules of the potential forwarders is Geographic Random Forwarding (GeRaF) [2], [3]. One problem identified in [2] and [3] is how to design a practical scheme to select a node to be the next-hop forwarder for a packet. In [2, Sec. 4], the authors present an ad hoc scheme based on partitioning the set of potential relays into "priority regions" based on distance from the destination. This scheme is then shown to offer performance close to the ideal case in which the best relay is always chosen. For fading channels with a channel coherence time that is on the order of the packet length, geographic routing will provide better performance than conventional routing protocols because pre-determined routes will often perform poorly because the specified links will often be in deep fades. In [4], the GeRaF scheme is extended to fading channels, with the same approach to finding "priority regions". In [17], Rossi *et al.* provide an adaptive framework for next-hop relay selection that can accommodate various cost functions but requires numerical optimization. In [18] and [19], node-activation probabilities are optimized to improve measures such as transmission distance. In [20], the authors consider the selection of an energy-efficient router in a Nakagami fading channel by considering both the maximum forwarding distance and the packet's successful transmission probability on a time-correlated channel.

Related to OpRx, *opportunistic transmission (OpTx)* can also take advantage of variations in the wireless channel by transmitting to a node that has a good channel gain (cf. [21]–[23]), thus achieving *multiuser diversity*. OpTx schemes, such as those in [24]–[27], are based on the approach in [21], in which the entire system bandwidth is allocated to the user with the best channel gain at each time and the power is simultaneously adapted to maximize the sum-rate capacity. Another type of OpTx is proposed in [28], in which mobility is used to move packets closer to their destinations. However, OpTx schemes are dependent on having packets available for many next-hop radios, having accurate channel-state information for the next-hop radios, and having packets that can tolerate additional latency. In fading wireless communication channels, the channel state may change too fast to allow for accurate updates in wireless mesh and sensor networks. Furthermore, many types of traffic cannot tolerate such delays, and the availability of appropriate packets is often limited by transport-layer protocols (cf. [29]).

In this paper, we develop a geographic transmission protocol that can achieve diversity through opportunistic reception. We consider a time-slotted scheme, which allows us to optimize the way in which potential relays contend to become the forwarder for a packet. Thus, we call our scheme Geographic Transmission with Optimized Relaying (GATOR). In Section II, we introduce the network model that we consider. In Section III, we present the GATOR protocol and derive the optimal relay selection scheme for GATOR when communication is over a Rayleigh fading channel. Section IV describes the transmission schemes that we use for performance comparisons, and Section V provides performance results. The paper is concluded in Section VI.

II. Network model

We consider a wireless mesh or sensor network, with fixed APs placed on a regular grid in a square area of dimension D km, as shown in Fig. 1. The APs are surrounded by nodes that wish to transmit information on the uplink to the APs. We assume that the nodes know their own locations and those of the APs and always send information to the nearest AP. We consider a scenario in which the APs are distributed in space with a sufficient density that packets have a high probability of reaching the AP in two hops for most nodes.

Time is assumed to be divided into frames, with nodes turning on and off from frame to frame to conserve energy. The APs are always on. In a given frame, the distribution of the nodes that are on (hereafter called "on-nodes") follows a homogeneous Poisson point process with density λ nodes per km^2. The process is assumed to be i.i.d. from frame to frame. When a node is on, it will generate a packet with probability p_s. Such a node is called a *source*. If an on-node does not have a packet to send, it will listen to transmissions from other nodes. If it successfully receives a packet from a source, it may remain on in the next time frame to contend to relay the packet to the AP. Otherwise, it may turn off in the next frame.

We further assume that the link for each transmitter-receiver pair is a frequency non-selective, slow Rayleigh fading Gaussian channel. The fading events for all the links are independent spatially and from frame to frame. The path-loss exponent is 2. Each node transmits at the same power, such that the average signal-to-noise ratio (SNR) at a receiver that is 1 km away is S_0.

Thus, the receive SNR in a time frame at distance d km from the transmitter is ZS_0d^{-2}, where Z is an exponential random variable with unit energy. For simplicity, we make the assumption that powerful channel coding is applied such that when a node sends a packet with information rate r bits/s/Hz to another node or an AP, the transmission will be successful if and only if the information rate is below the capacity of the link in that frame. That is, transmission through the link is successful if and only if $r < \log_2(1 + ZS_0d^{-2})$. For convenience, define the rate-normalized SNR $S_r \triangleq \frac{S_0}{2^r-1}$. Then a transmission is successful if $Z > \frac{d^2}{S_r}$.

III. Geographic Transmission with Optimized Relaying (GATOR)

GATOR is designed for mesh networks in which a relay can be employed if a packet is not received directly by the AP. The focus of our work is on the problem of determining which nodes should compete as relays and how they should compete if a fixed number of slots within each frame are available for contention. We assume that nodes know their locations and whether they have received the packet correctly, but they do not know the channel fading gain to the AP. Thus, we propose a geographic strategy in which nodes use their location information and that of the AP in determining whether and how to contend for the channel. Unlike conventional fixed routing, the relay is not pre-determined. Thus, this is an opportunistic reception scheme that may be able to extract additional diversity from the channel.

In GATOR, time is divided into consecutive frames of equal duration and structure. The structure for one frame is shown in Fig. 2(a). There are two sets of mini-slots at the beginning of each frame that are used to contend for the channel. The first M mini-slots are used by potential relays to contend to forward a packet that was not received at the AP in the previous frame. The remaining K mini-slots are for sources that have a packet to send to contend for the channel. We describe the use of these mini-slots from a source's perspective first. Relaying is given priority, so a source will first sense the channel during the M mini-slots before contending for the channel in the remaining K mini-slots. If a source does not sense any signals in the first M slots, then the source will select a uniform random number between 1 and K. If a source selects i, then it will sense the channel in mini-slots 1 to $i-1$. If a carrier signal is detected in those mini-slots, then the source will not transmit its data in the current frame and will compete for the channel again in the next frame. If no carrier is detected in these mini-slots, the source will send a carrier in mini-slot i to indicate that it has acquired the channel and will transmit its packet in the "Data Packet" slot. The remaining slots in the frame are for data transmission and acknowledgments. A packet may be directly received by the destination AP, in which case the AP sends an AP-ACK (AACK). If the AACK is received, the source deletes the successful packet from its buffer.

If the AACK is not received, the source will sense the channel in the M mini-slots in the next frame. If no signal is detected in the M mini-slots, then the source will assume that neither the source nor any relay received the packet, and it will contend for the channel again. If a signal is detected in the M mini-slots, then the source will listen to the data packet to see if its packet is being relayed. If the AP receives a packet from a relaying node, it will send an AACK, and the relay will send a Relay-ACK (RACK) back to the source. Note that we assume that the rate of information in the ACK signals is substantially lower than that of the data packet. Hence with the use of powerful channel coding, the ACK signals can be successfully received by the source even when direct data packet transmission from source to the AP fails.

Now consider the problem of determining which of the non-source nodes should contend to relay a packet (i.e., become potential relays) and how those potential relays should use the M mini-slots to contend to forward a packet. To avoid collision, one and only one of the on-nodes that has received the packet should relay it to the AP. To maximize the probability that the relay's transmission to the AP is successful, it is desirable to choose a relay that is close to the AP. However, such nodes are generally relatively far from the source, which results in such nodes having a small probability of having correctly received the packet. We wish to optimize the relay selection scheme in GATOR to balance between these factors. For mathematical tractability, we focus on a single source in Section III-A. In Section III-B, we discuss the extension of GATOR to multiple sources and APs, and in Section V we use simulation to evaluate the performance with multiple sources and multiple APs.

A. Optimal Relay Regions for a Single Source

Consider a single source transmitting to an AP. We assume that after this source successfully contends for channel use, no other sources in the whole network will send any packets. Without loss of generality, suppose that the source is located at $(-d, 0)$ and the nearest AP is located at $(0, 0)$, as shown in Fig. 3. If the packet transmission from the source directly to the AP failed in the previous time frame (indicated by the absence of an AACK), all on-nodes that have successfully received the packet contend for forwarding it to the AP based on the following protocol in the current time frame:

1) An on-node that has successfully received the packet from the source picks a random number $N(x, y)$ from the set $\{1, 2, \ldots, M, M + 1\}$ according to the probability mass function (pmf) $p_m(x, y)$ for $m = 1, 2, \ldots, M + 1$, where (x, y) is the location of the node.
2) If $N(x, y) = M + 1$, the node will not forward the packet.
3) If $N(x, y) \leq M$, then the node senses the channel during mini-slots 1 to $N(x, y) - 1$. If the node detects a carrier signal in any of these $N(x, y) - 1$ mini-slots, it will not forward the packet. If no other nodes transmit during these mini-slots, the node will send a carrier signal in mini-slot $N(x, y)$, and then forward the data packet in the data slot of the frame.

Note that if more than one on-node sends a carrier signal in the same mini-slot, the data transmissions from these nodes will collide. Thus the optimal forwarding resolution design provides the pmf $p_m(x, y)$ that maximizes the probability P_F of the event that exactly one on-node forwards to the AP and succeeds in doing so in the time frame after the packet transmission from the source. For simplicity, we make the assumption that the required SNR to detect a carrier signal is very low so that all carrier signals can be detected by all on-nodes in the network.

To calculate P_F, let us partition the plane into rectangles of infinitesimal area $dxdy$. For the rectangle at (x, y) and an on-node inside this rectangle, the probability that this node successfully receives the packet from the source and the node selects $N(x,y)=m$ is $p_m(x,y)\cdot e^{-[(x+d)^2+y^2]/S_r}$. Thus the probability that no node in the rectangle at (x,y) forwards the packet to the destination is

$$\sum_{n=0}^{\infty}\frac{(\lambda dxdy)^n e^{-\lambda dxdy}}{n!}\left[1-e^{-\frac{[(x+d)^2+y^2]}{S_r}}\sum_{i=1}^{m}p_i(x,y)\right]^n=\exp\left[-\lambda e^{-\frac{[(x+d)^2+y^2]}{S_r}}\sum_{i=1}^{m}p_i(x,y)dxdy\right],$$

and the probability that exactly one on-node in this rectangle selects an $N(x,y)=m$ and all other on-nodes in this rectangle select $N(x,y)>m$ (that is, exactly one on-node in this rectangle forwards) is

$$\begin{aligned}&\sum_{n=0}^{\infty}\frac{(\lambda dxdy)^n e^{-\lambda dxdy}}{n!}\binom{n}{1}\left[p_m(x,y)e^{-[(x+d)^2+y^2]/S_r}\right]\cdot\left[1-e^{-[(x+d)^2+y^2]/S_r}\sum_{i=1}^{m}p_i(x,y)\right]^{n-1}\\ =\;&\lambda p_m(x,y)e^{-[(x+d)^2+y^2]/S_r}dxdy\cdot\exp\left[-\lambda e^{-[(x+d)^2+y^2]/S_r}\sum_{i=1}^{m}p_i(x,y)dxdy\right].\end{aligned}$$

Therefore the probability that exactly one node at (x,y) picks an $N(x,y)=m$ but no node at any location picks an $N(\tilde{x},\tilde{y})\le m$ (that is, exactly one node at (x,y) forwards but no nodes at other locations forward) is

$$\begin{aligned}&\lambda p_m(x,y)e^{-[(x+d)^2+y^2]/S_r}dxdy\cdot\exp\left[\iint -\lambda e^{-[(\tilde{x}+d)^2+\tilde{y}^2)]/S_r}\sum_{i=1}^{m}p_i(\tilde{x},\tilde{y})d\tilde{x}d\tilde{y}\right]\\ =\;&\lambda p_m(x,y)e^{-[(x+d)^2+y^2]/S_r}dxdy\cdot\exp\left[-\lambda\iint e^{-[(\tilde{x}+d)^2+\tilde{y}^2)]/S_r}\sum_{i=1}^{m}p_i(\tilde{x},\tilde{y})d\tilde{x}d\tilde{y}\right].\end{aligned}$$

Finally, we have

$$P_F=\sum_{m=1}^{M}\left[\lambda\iint e^{-\Delta(x,y)}p_m(x,y)dxdy\right]\cdot\exp\left[-\lambda\iint e^{-\Xi(x,y)}\sum_{i=1}^{m}p_i(x,y)dxdy\right],$$

where $\Xi(x,y)=\frac{(x+d)^2+y^2}{S_r}$, $\Gamma(x,y)=\frac{x^2+y^2}{S_r}$, and $\Delta(x,y)=\Xi(x,y)+\Gamma(x,y)$.

We consider the maximization of P_F subject to $g_m(x,y)=-p_m(x,y)\le 0$ for $m=1,2,\ldots,M$ and all (x,y), and $g(x,y)=\sum_{m=1}^{M}p_m(x,y)-1\le 0$ for all (x,y). Note that P_F is concave, and $g_m(x,y)$ and $g(x,y)$ are linear in $\{p_m(x,y):m=1,2,\ldots,M \text{ and all } (x,y)\}$. Thus the KKT condition [30] gives the optimal choice of $p_m(x,y)$ necessarily and sufficiently. First consider the Lagrange function as

$$L=P_F+\sum_{m=1}^{M}\iint\mu_m(x,y)g_m(x,y)dxdy+\iint\mu(x,y)g(x,y)dxdy.$$

The element in the gradient vector of the Lagrangian corresponding to $p_k(x,y)$ is

$$\frac{\partial L}{\partial p_k(x,y)} = \frac{\partial P_F}{\partial p_k(x,y)} + \sum_{m=1}^{M} \iint \mu_m(x,y) \frac{\partial g_m(x,y)}{\partial p_k(x,y)} dxdy + \iint \mu(x,y) \frac{\partial g(x,y)}{\partial p_k(x,y)} dxdy$$

$$= \mu(x,y) - \mu_k(x,y) + \lambda e^{-\Xi(x,y)} dxdy \Bigg\{ - \sum_{m=k}^{M} \lambda \left[\iint e^{-\Delta(x,y)} p_m(x,y) dxdy \right]$$

$$\cdot \exp\left[-\lambda \iint e^{-\Xi(x,y)} \sum_{i=1}^{m} p_i(x,y) dxdy \right] + e^{-\Gamma(x,y)} \cdot \exp\left[-\lambda \iint e^{-\Xi(x,y)} \sum_{i=1}^{k} p_i(x,y) dxdy \right] \Bigg\}$$

for $k = 1, 2, \ldots, M$ and all (x,y). Define

$$K(R_u, R_l) = 2\pi\lambda e^{-d^2/S_r} \int_{R_l}^{R_u} \rho e^{-2\rho^2/S_r} I_0\left(\frac{2\rho d}{S_r}\right) d\rho$$

$$L(R_u, R_l) = 2\pi\lambda e^{-d^2/S_r} \int_{R_l}^{R_u} \rho e^{-\rho^2/S_r} I_0\left(\frac{2\rho d}{S_r}\right) d\rho,$$

where $I_0(\tau) = \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{\tau\cos\theta} d\theta$ is the zeroth-order modified Bessel function of the first kind, and let $R_1, R_2, \ldots, R_M$ be the solution of the following sets of nonlinear equations of the Lagrangian:

$$\begin{aligned}
e^{-R_M^2/S_r} &= K(R_M, R_{M-1}) \\
e^{-R_{M-1}^2/S_r}\left[1 - e^{-L(R_M, R_{M-1})}\right] &= K(R_{M-1}, R_{M-2}) \\
e^{-R_{M-2}^2/S_r}\left[1 - e^{-L(R_{M-1}, R_{M-2})}\right] &= K(R_{M-2}, R_{M-3}) \\
&\vdots \\
e^{-R_1^2/S_r}\left[1 - e^{-L(R_2, R_1)}\right] &= K(R_1, 0).
\end{aligned}$$

Then we have $0 \triangleq R_0 \le R_1 \le R_2 \le \cdots \le R_M < R_{M+1} \triangleq \infty$. The values of $R_1, R_2, \ldots, R_M$ can be obtained numerically by a simple iterative algorithm:

1) Set $R_1 = R_2 = \cdots = R_{M-1} = 0$.
2) Numerically solve the first equation to get R_M.
3) Use this value of R_M in the second equation to solve for R_{M-1}.
4) Continue this way to solve for $R_{M-2}, R_{M-3}, \ldots, R_1$ until reaching the last equation.
5) Repeat Steps 2–4 with the new set of values for the R_m's until they converge.

Now consider, for $k = 1, 2, \ldots, M$,

$$p_k(x,y) = \begin{cases} 1 & \text{if } R_{k-1}^2 < x^2 + y^2 \le R_k^2 \\ 0 & \text{otherwise,} \end{cases}$$

$$\mu_k(x,y) = \begin{cases} 0 & \text{if } x^2+y^2 > R_{k-1}^2 \\ \lambda e^{-\Xi(x,y)} dxdy \cdot e^{-L(R_{k-l},0)} \cdot & \\ \quad \Big\{ e^{-\Gamma(x,y)} \left[1 - e^{-L(R_k, R_{k-l})} \right] & \text{if } R_{k-1-l}^2 < x^2+y^2 \le R_{k-l}^2 \\ \quad\quad - \sum_{m=k-l}^{k-1} K(R_m, R_{m-1}) e^{-L(R_m, R_{k-l})} \Big\} & \text{for } l = 1, 2, \ldots, k-1, \end{cases}$$

and

$$\mu(x,y) = \begin{cases} 0 & \text{if } x^2+y^2 > R_M^2 \\ \lambda e^{-\Xi(x,y)} dxdy \cdot e^{-L(R_l,0)} \cdot & \text{if } R_{l-1}^2 < x^2+y^2 \le R_l^2 \\ \quad \Big\{ e^{-\Gamma(x,y)} - \sum_{m=l}^{M} K(R_m, R_{m-1}) e^{-L(R_m, R_l)} \Big\} & \text{for } l = M, M-1, \ldots, 1. \end{cases}$$

Then $\mu_k(x,y) \ge 0$ and $\mu(x,y) \ge 0$ for all $k = 1, 2, \ldots, M$ and all (x,y). In addition, since dx and dy are infinitesimally small, we have

$$\begin{aligned} \frac{\partial L}{\partial p_k(x,y)} &= \lambda e^{-\Xi(x,y)} dxdy \cdot \left\{ \sum_{m=k}^{M} K(R_m, R_{m-1}) e^{-L(R_m,0)} - e^{-\Gamma(x,y) - L(R_k,0)} \right\} - \mu_k(x,y) + \mu(x,y) \\ &= 0, \end{aligned}$$

$\mu_k(x,y) g_k(x,y) = 0$, and $\mu(x,y) g(x,y) = 0$, for all $k = 1, 2, \ldots, M$ and all (x,y). As a result, if we define $R_{M+1} = \infty$, then

$$p_k(x,y) = \begin{cases} 1 & \text{if } R_{k-1}^2 < x^2 + y^2 \le R_k^2 \\ 0 & \text{otherwise,} \end{cases}$$

where $k = 1, 2, \ldots, M, M+1$, maximizes P_F. Hence the maximum P_F is given by

$$\begin{aligned} P_F &= \sum_{m=1}^{M} K(R_m, R_{m-1}) e^{-L(R_m,0)} \\ &= e^{-L(R_1,0)} - \sum_{m=1}^{M} e^{-L(R_m,0)} \cdot \left[e^{-R_{m-1}^2/S_r} - e^{-R_m^2/S_r} \right]. \end{aligned}$$

Physically, the optimal choice of pmf above suggests a (deterministic) forwarding resolution mechanism depicted in Fig. 3. Consider rings centered at the information AP defined by the radii $R_1, R_2, \ldots, R_M$ above. An on-node that has successfully received the packet transmitted from the source can use the location information (locations of the source and AP) in the packet to determine in which ring it lies. The on-nodes in the rings closest to the destination have higher priority to forward the packet from the source than those on-nodes in the outer rings. This priority is asserted by transmitting a carrier signal in the proper mini-slot: on-nodes in the ring with outer radius R_i use mini-slot i, where on-nodes outside R_M will not forward the packet. Thus, we evaluate the performance of the above P_F-maximizing choice of $p_m(x, y)$ in terms of the average delay D, measured in terms of the number of time frames required to send the packet from the source to the destination, which is given by

$$D = \sum_{k=1}^{\infty} k P_k,$$

where P_k is the probability that the destination successfully receives the packet in the kth time frame. Note that the probability that the source transmits to the destination directly and successfully is given by e^{-d^2/S_r}, which is obtained from the non-outage event, $\log(1+ZS_0 d^{-2}) \geq r$. For $k = 1, 2, \ldots$,

$$\begin{aligned} P_{2k-1} &= \left[1 - e^{\frac{-d^2}{S_r}} - (1 - e^{\frac{-d^2}{S_r}})P_F\right]^{k-1} \cdot e^{\frac{-d^2}{S_r}} \\ P_{2k} &= \left[1 - e^{\frac{-d^2}{S_r}} - (1 - e^{\frac{-d^2}{S_r}})P_F\right]^{k-1} \cdot \left[1 - e^{\frac{-d^2}{S_r}}\right] P_F. \end{aligned}$$

Hence

$$D = \sum_{k=1}^{\infty} (2k-1) P_{2k-1} + \sum_{k=1}^{\infty} 2k P_{2k} = \frac{2 - e^{-d^2/S_r}}{e^{-d^2/S_r} + \left[1 - e^{-d^2/S_r}\right] P_F}.$$

The ring-based forwarding resolution protocol above also minimizes the average number of time slots needed for a packet to traverse from the source to the AP in geographic transmission. This proves the optimality of the "priority regions" in [2] and [4] for sources close to the destination with path-loss exponent 2 and Rayleigh fading, and, more importantly, provides a solution to the dimension of the priority regions when the time-slotted GATOR protocol is used.

B. Extension to Multiple Sources and APs

In a practical application of GATOR, there are multiple sources and APs, as shown in Fig. 1. Here, we describe how we deal with the impact of multiple sources and APs in GATOR. First, we consider the detection of carrier signals in the carrier-reservation mini-slots. The instantaneous SNR of carrier signals received at any radio node can be obtained by

$$SNR_{CS} = \left(\sum_i \sqrt{SNR_{CS_i}} \cos\theta_i \right)^2 + \left(\sum_i \sqrt{SNR_{CS_i}} \sin\theta_i \right)^2$$

where SNR_{CS_i} denotes the received SNR of a carrier signal from a node i, and θ_i denotes the random phase of the link between transmitter node i and the receiver. We assume that a carrier will be detected if and only if $SNR_{CS} > S_{th}$, where S_{th} is a threshold that depends on the SNR parameter S_0, the packet generation rate p_s and the density of nodes λ. S_{th} is chosen based on simulation results to balance between the probability of false alarm (dominated by detecting carrier signals intended for a different AP) and the probability of miss (not detecting a carrier signal intended for the nearest AP to the receiver).

The optimal forwarding regions described above are for a network with a single source at a fixed location and a single AP. In a network with multiple sources and multiple APs, packet transmissions from multiple sources and relays may occur in the same frame, and therefore we need to consider the signal-to-interference-noise ratio (SINR) of a source's transmission to find the optimal forwarding regions rather than the SNR. The received SINR at the intended AP is

$$SINR_{RX} = \frac{SNR_{RX}}{\sum_{i=1}^{N_S} SNR_i + \sum_{j=1}^{N_R} SNR_j + 1}$$

where SNR_{RX} denotes the received SNR of the packet transmission from the source to the intended AP, and SNR_i and SNR_j, respectively, denote the received SNR at the AP of interfering packet transmissions from the other sources and relays. Here N_S and N_R also denote the number of interfering transmissions from sources and relays, respectively. The optimal forwarding regions will depend on the SINR at the AP as well as the distance from the source to the AP. Thus for GATOR with multiple sources and APs, when a source gains access to the channel, we use the known distance to the AP and the computed average SINR for the given system parameters to determine the relaying regions (these can be independently computed at each of the potential relays that correctly recover a packet).

IV. Comparison Transmission Schemes

We have selected two conventional (non-geographic) communication schemes and two geographic communication schemes based on GeRaF for which we will compare the performance with that of GATOR.

A. Conventional Schemes

The first conventional scheme is *direct transmission*, in which the source transmits to the nearest AP with no relaying allowed. The time slot structure used for this protocol is shown in Fig. 2(b). Sources contend for the channel as described in Section III, and simply re-transmit packets after transmission failure.

In the second conventional scheme, *fixed routing*, we assume that there is always a router placed midway between a source and the corresponding AP. Since the router is optimally placed, this should give the best possible performance among any conventional routing approach. The slot structure for routing is shown in Fig. 2(c). Sources contend for the channel in the same way as in GATOR (cf. Section III). If the AP correctly receives a packet from a source, it sends an acknowledgment in the AACK mini-slot. If the router does not hear the AACK signal and has successfully received the packet, it will send a RACK. Then the router will take over responsibility for delivering the packet. If either the AACK or the RACK is received, the source deletes the packet from its buffer. All sources and routers employ the channel contention protocol in Section III to contend for channel use or re-transmit packets after transmission failure.

B. Geographic Transmission Schemes

The first geographic transmission scheme is based on GeRaF [2]–[4] with modifications to make GeRaF utilize a time-slotted structure. We refer to this as Slotted GeRaF (S-GeRaF). The frame structure used for S-GeRaF is shown in Fig. 2(d). The first mini-slot is the Request-for-Relay (RR) mini-slot, which is used by potential relay nodes that have received a packet from a source to contend to forward the packet to the AP: nodes that have received a packet from a source transmit a carrier in this mini-slot to reserve the channel for forwarding. If no carrier signal is detected in the RR mini-slot, sources contend for the channel as described in Section III. A source that has acquired the channel uses the RTS/CTS-based collision avoidance protocol [3] with the relay regions described in [4] to find a single relay node. The relay region contains M priority regions, and the ith priority region, B_i, is a circular ring centered on the destination with radii R_{i-1} and R_i. The R_i's are selected such that the average number of "available potential relays" in each priority region is the same, with the initial conditions that R_0 is equal to zero, and R_M is equal to the distance between a source and the nearest AP. Thus, the R_i's satisfy

$$\int_{B_i} \lambda P(\rho) d\rho = \int_{B_{i-1}} \lambda P(\rho) d\rho \quad i = 2, ..., M,$$

where $P(\rho) = P(Z > \frac{\rho^2}{S_r})$ is the probability that a transmission from a source to a potential relay at the distance ρ away from the source is successful. The source then transmits a broadcast RTS message and listens in the subsequent slot for CTS messages from potential relays located in the innermost priority region. If only one CTS message is received, the source will send a STOP message and stop the collision avoidance protocol operation. If the source receives no CTSs, it will send a CONTINUE message and listen again for CTSs from potential relays located in the next priority region. If the source hears a signal but is not able to detect the message, it will assume that a CTS collision occurs, and will send a COLLISION message which will initiate a collision resolution algorithm [3]. To limit the duration of the collision avoidance protocol, it terminates if the CTS collision is not resolved within N RTS/CTS slots. If the source receives a CTS message from only one potential relay node within N RTS/CTS slots, the source transmits the packet to the relay in the "Data Packet" slot. A packet may be directly received by the destination AP, in which case the AP sends an ACK. If the ACK is received, the source can delete the successful packet from its buffer. If the ACK is not received, the source will sense the channel in the RR mini-slot in the next slot. If no signal is detected, then the source will assume that neither the AP nor the relay received the packet, and it will contend for the channel again. A source that did not transmit in a previous slot will also sense the channel in the RR mini-slot. If a carrier signal is detected in the RR mini-slot, the source will transmit neither a carrier nor a RTS message, and the source will listen to the data packet to see if its packet is being relayed. If the AP receives a packet from a relay node, it will send an ACK to the source, and the source will delete the packet from its buffer.

The second geographic transmission scheme uses the protocol of GATOR but with the relay regions of GeRaF. We refer to this as GATOR with GeRaF-based relay regions (GATOR-GBRR).

V. Simulation results

In this section, we compare the performances of GATOR and the comparison protocols specified in Section IV in a mesh network, as shown in Fig. 1. For all of the results presented, the dimension of the network is 24 km $\times$ 24 km, and $r = 1$ bits/s/Hz. Except for the results in Figs. 9 and 10, the node density is $\lambda = 10\ \mathrm{nodes/km}^2$ and the rate-normalized SNR is 10. To avoid the edge effect caused by having a finite simulation field, we allow the boundaries to wrap around, such that the top and bottom edges become adjacent, as do the left and right edges of the grid. For each protocol, we consider the best performance over all offered loads by finding the value of p_s that maximizes the throughput of the network, where the throughput is defined as the average total number of packets successfully delivered to the APs per time slot. Since the different protocols require different numbers of mini-slots (protocol overhead), we plot normalized throughputs relative to the direct transmission scheme with no contention slots (i.e., just Data+ACK). The normalized throughput is the throughput per slot divided by the length of the slot relative to direct transmission. The throughput reduction is based on the parameters in Table I. For instance, when $K = 16$ and $M = 16$, the slot time for GATOR is 1.16

times (=10,640 μs / 9,200 μs) longer than the slot time without any overhead, and the effective throughput is the per-slot throughput divided by 1.16. We also limit the maximum number of times a source will transmit a packet to 4, after which the packet will be dropped.

In Fig. 4, we show the throughput of the various schemes, as a function of the number of APs. We show the performance of GATOR and GATOR-GBRR for several values of M, the number of mini-slots used by the relays. For all these results, the number of mini-slots used by sources to contend for the channel is K=16. For a given number of APs, the maximum throughput of geographic transmission increases with an increase in M until M=32. The reason is that, as M increases, the potential relays that are closer to the AP have higher priority to forward the packet to the AP than those potential relays that are farther, and the probability of collision is reduced. However, beyond M=32 the maximum throughput of geographic transmission starts decreasing since the increased overhead exceeds any additional throughput gain. For all numbers of APs and M, GATOR significantly outperforms direct transmission, fixed routing, S-GeRaF, and GATOR-GBRR. For S-GeRaF, we show the best performance that we found after varying the number of source-contention slots M and RTS/CTS slots N (see Fig. 5 for supporting results).

The results in Fig. 6 show the throughput effects of varying K, the number of source contentions slots, as the number of APs is also varied. For GATOR and GATOR-GBRR the number of mini-slots used for relay selection, M, is 32. For the values of K until 16, the performance of all four schemes increases. This is reasonable, as increasing K increases the probability of scheduling exactly one source to send a carrier signal for channel access. However, once K reaches 32, the throughput of all four schemes decreases because the increase in overhead exceeds the additional gains in throughput.

As previously mentioned, we limit the number of times a packet can be transmitted, as is typical in most systems. The results in this paper assume that a packet can be transmitted from a source a maximum of 4 times. An important issue then is how the various protocols impact the probability of packet drop, which occurs when a source reaches the maximum number of transmissions for a packet without it being successfully received at the AP. To investigate this effect, we limited the maximum distance of the sources from the APs, and in Fig. 7 we show the probability of packet drop as a function of this maximum distance. For these results, the number of APs is 4, M=32 for GATOR and GATOR-GBRR, and M=8 and N=10 in S-GeRaF. The benefits of geographic transmission over direct transmission and fixed routing schemes are particularly dramatic. This can be attributed to the fact that geographic transmission is able to extract high orders of diversity from the channels to the destination and potential relays, whereas direct transmission and fixed routing are limited to diversity order 1 and 2, respectively. GATOR achieves significantly better performance than S-GeRaF or GATOR-GBRR. In Fig. 8, we show the probability of a source reaching the maximum number of transmissions as function of the number of APs. Again, the geographic transmission schemes provide much better performance than direct transmission or fixed routing, and GATOR outperforms S-GeRaF and GATOR-GBRR.

The results in Fig. 9 show the effects of varying the SNR parameter S_0 on throughput, for different numbers of APs. The performance of S-GeRaF is not shown, since it is inferior to GATOR-GBRR. The results show that GATOR provides the best throughput out of all the schemes for all number of APs and SNR parameters we considered. Except for small numbers of APs (1 and 4) combined with $S_0 = 20$ dB, GATOR offers significantly better throughput than the other schemes. For large S_0, the gain of the geographic schemes over direct transmission and fixed routing decreases, as the average SNR at the AP and router become sufficiently high that the higher diversity of geographic transmission offers less benefit. The maximum throughput of direct transmission increases with an increase in S_0, but the throughput is significantly less than those of geographic transmission and fixed routing scheme even for S_0=20 dB.

Next, we evaluate the impact of the density of on-nodes on the throughput of the protocols, the results of which are shown in Fig. 10. For a given number of APs, the throughputs of GATOR and GATOR-GBRR increase with an increase in λ over the range we investigated. This is because the GATOR schemes are effective at extracting increased orders of multiuser diversity from the larger number of potential relays.

An area of concern for geographic communication protocols is whether the additional throughput gains are achieved by consuming additional energy. Compared to direct transmission, the geographic communication protocols utilize additional energy in relaying and in the relay contention phase. Thus, we consider the energy efficiency of the various schemes, measured by the energy per successful packet, E_p, which is defined as the ratio of the total energy consumption over all nodes and APs in the network to the total number of packets successfully delivered to the APs. E_p is measured in Joules/packet. The total energy consumption is the sum of each node's and AP's energy consumption for packet, carrier signal, control message and ACK transmissions during the simulation time. The noise power is assumed to be 1 mW for calculating a signal power and energy consumption from SNR parameters. The packet-normalized energies of the various schemes schemes are shown in Fig. 11 as a function of the number of the APs. For all numbers of APs, GATOR achieves the lowest packet-normalized energy. GATOR offers the largest performance gains when the number of APs is small. For large numbers of APs, the probability of success on a direct transmission increases sufficiently that the benefits of geographic transmission decrease.

VI. CONCLUSION

In this paper, we considered the design of a geographic communication scheme to achieve opportunistic reception in a mesh network with block-fading channels. We introduced a time-slotted protocol framework, and considered the problem of relay selection in that framework. We showed that we can cast the relay selection problem as a convex optimization problem, the solution of which results in dividing space into a series of concentric rings centered on the AP. A receiver that successfully overhears a message will contend to act as a forwarder for the packet with probability 1 in a mini-slot that corresponds to the index of the ring in which the receiver lies. The resulting scheme is the geographic transmission with optimized relaying (GATOR) protocol. We compared the performance of GATOR to direct transmission, fixed routing with a router optimally placed midway between the source and AP, a slotted version of GeRaF, and GATOR with relaying regions chosen as in GeRaF. We compared the performance with many different system parameters, and evaluated the performance in terms of different metrics, such as throughput, probability of reaching the maximum number of allowed transmissions for a packet, and energy efficiency. The results show that GATOR offers the best performance of all of the schemes in all of the scenarios considered.

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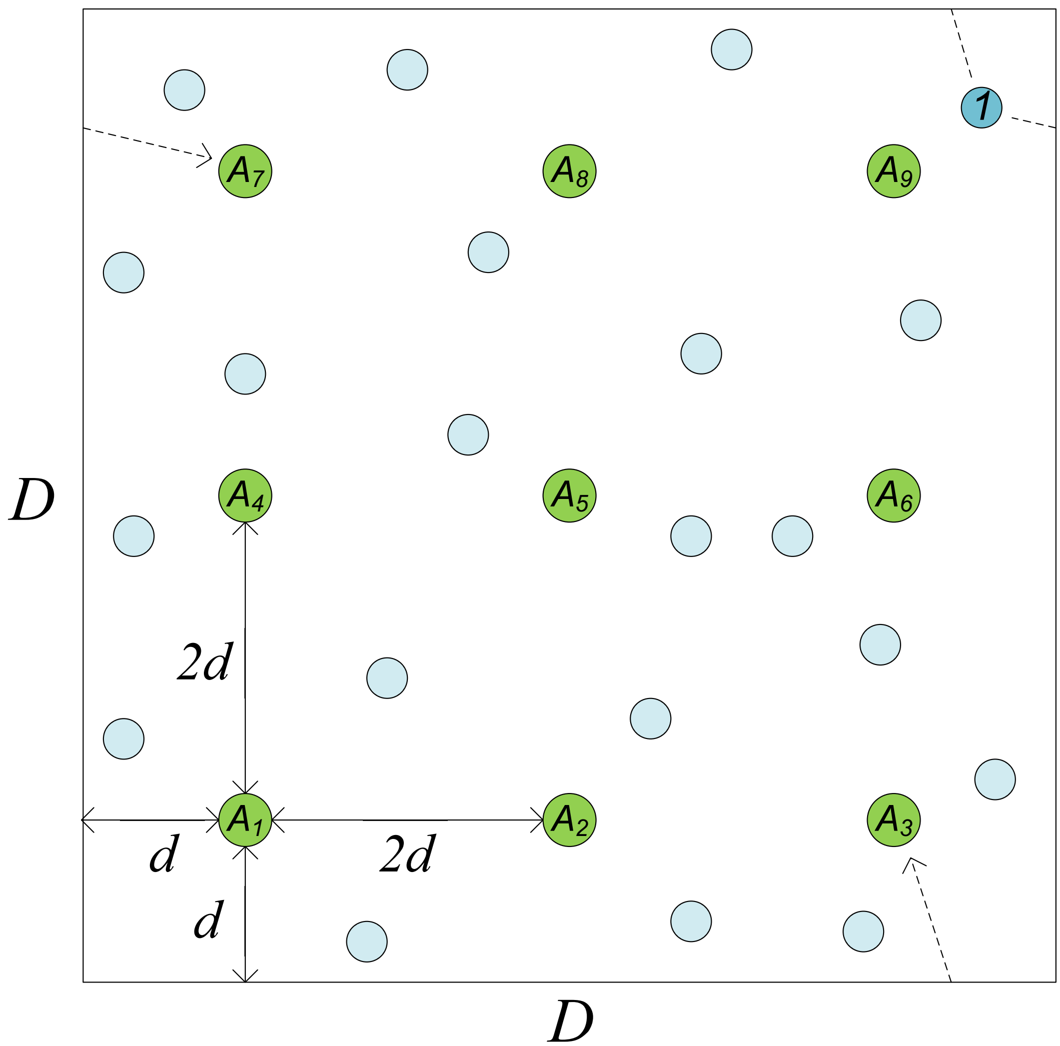
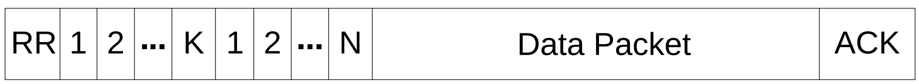


Fig. 1. Example of mesh network layout with 9 access points. A_i = i-th access point.

(a) Geographic Transmission with Optimized Relaying (GATOR).

(b) Direct transmission.

(c) Routing.



(d) S-GeRaF.

Fig. 2. Structure of one time frame for the protocols in this paper.

TABLE I

PARAMETERS USED FOR CALCULATING THROUGHPUT PENALTIES OF ROUTING AND GEOGRAPHIC-TRANSMISSION TECHNIQUES RELATIVE TO DIRECT TRANSMISSION.

Parameter	Default value
Bandwidth	1 MHz
Data rate	1 Mbps
Data	1,000 bytes
ACK data	50 bytes
RTS/CTS data	50 bytes
Control message data	50 bytes
PLCP header	16 bytes
MAC header	34 bytes
$t_{\rm data}$ (PLCP header+MAC header+data)	8,400 μs
$t_{\rm ACK}$ (PLCP header+MAC header+ACK data)	800 μs
$t_{\rm RTS/CTS}$ (PLCP header+MAC header+RTS/CTS data)	800 μs
$t_{\rm CNT}$ (PLCP header+MAC header+control message data)	800 μs
$t_{\rm mini-slot}$ (Slot time)	20 μs

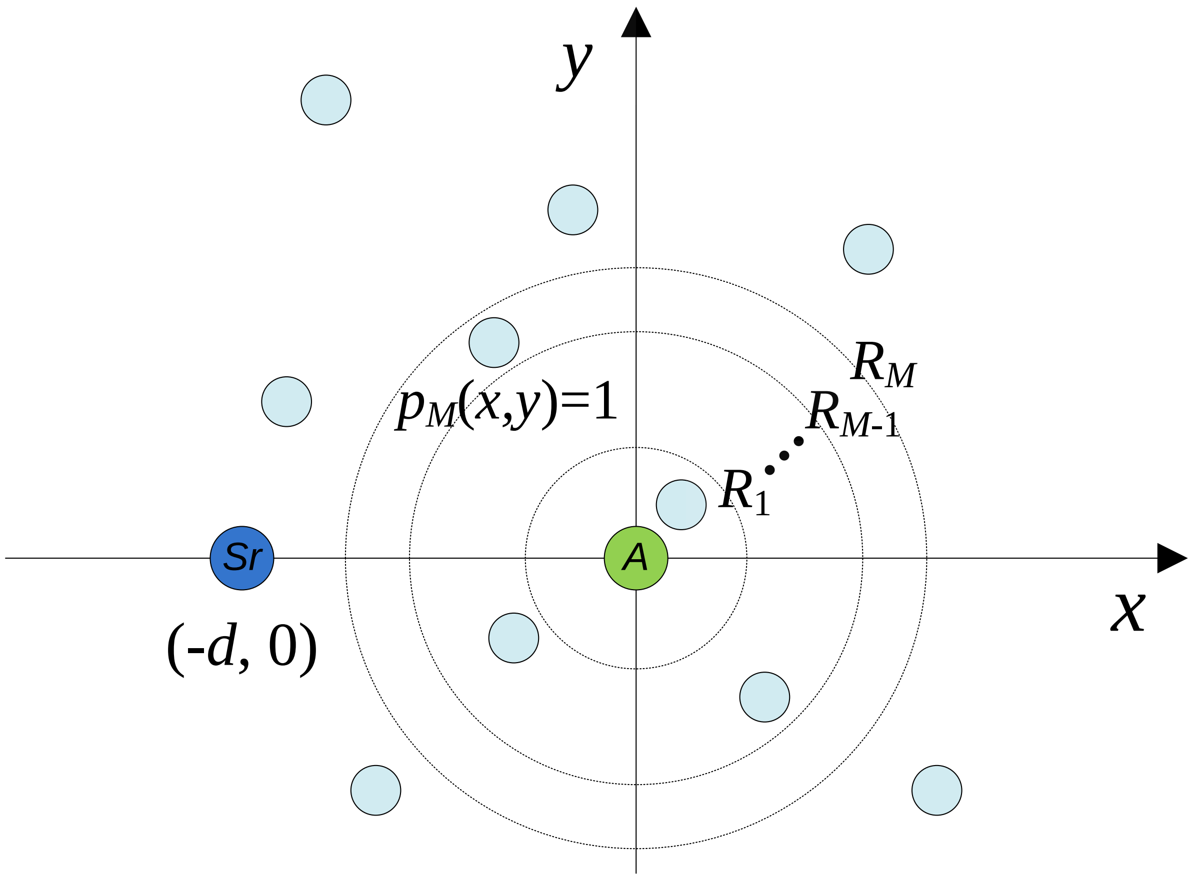


Fig. 3. Illustration of optimal forwarding resolution protocol in geographic transmission. S_r = source node. A = access point.

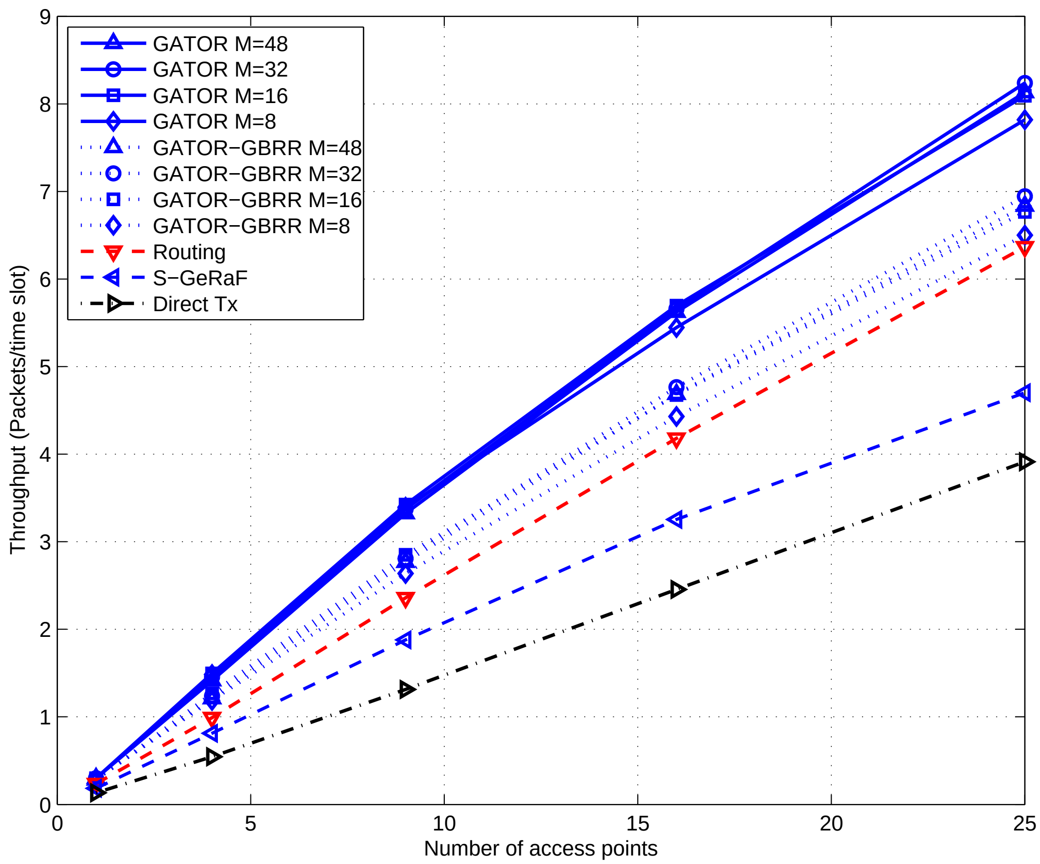


Fig. 4. Throughput vs. number of access points for various numbers of forwarding regions, M. The average SNR is S_0=10 dB, and the number of carrier-reservation mini-slots used by sources is K=16. For S-GeRaF, the best combination of the number of forwarding regions ($M = 8$) and the number of RTS/CTS slots ($N = 10$) was used – see Fig. 5.

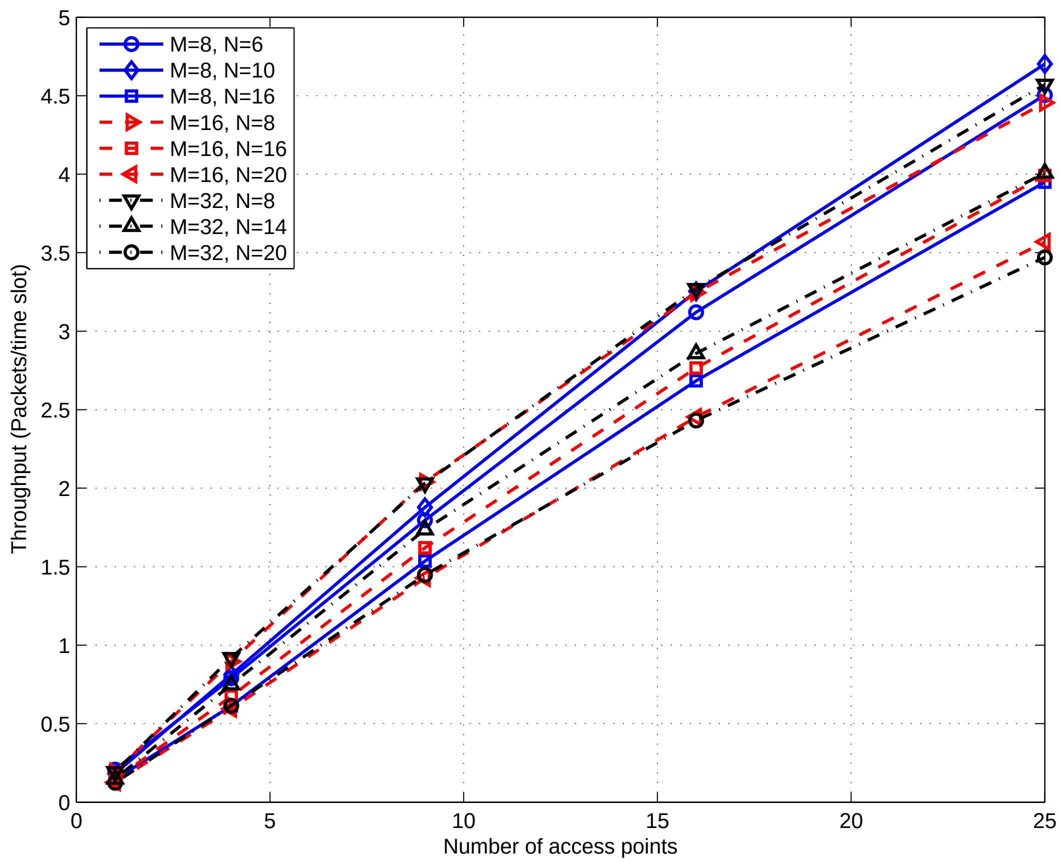


Fig. 5. Throughput of S-GeRaF vs. number of access points for various numbers of forwarding regions, M, and RTS/CTS slots, N, for the collision avoidance protocol. The average SNR is S_0=10 dB, and the number of carrier-reservation mini-slots used by sources is K=16.

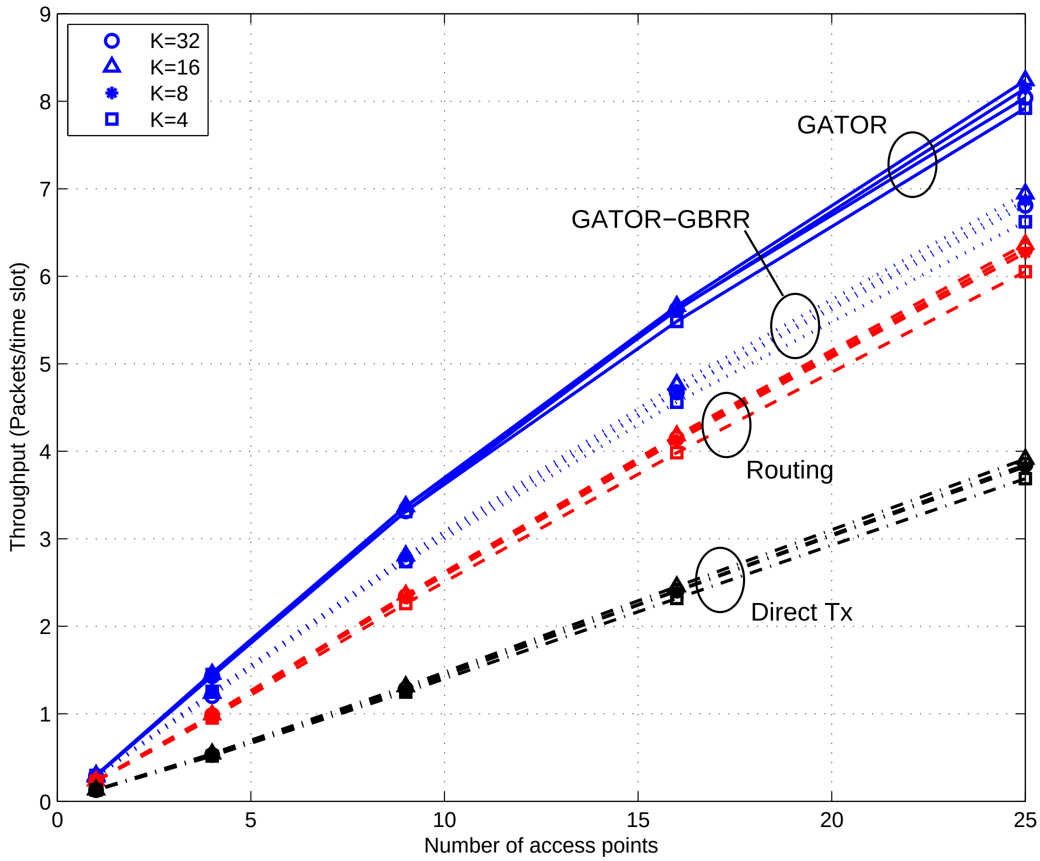


Fig. 6. Throughput vs. number of access points for various numbers of carrier-reservation mini-slots used by sources, K. The average SNR is S_0=10 dB, and the number of forwarding regions is M=32.

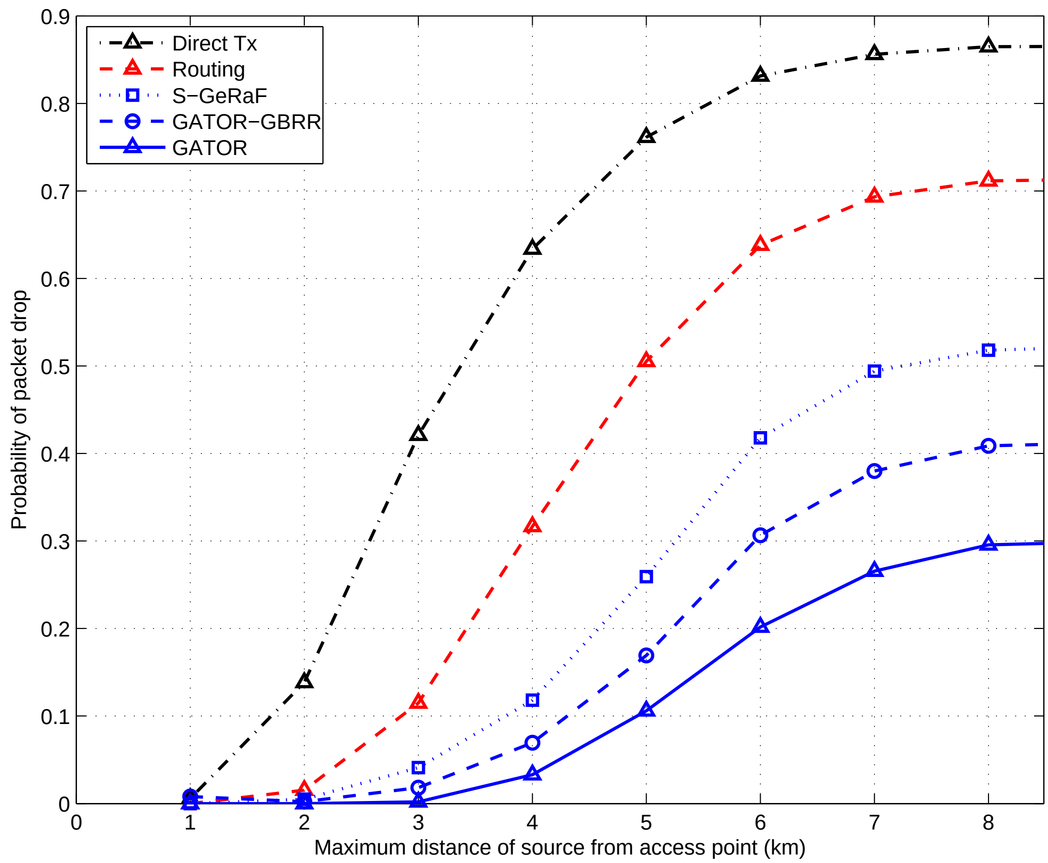


Fig. 7. Probability of packet drop from source reaching maximum number of transmissions ($N_{tx} = 4$) vs. maximum distance from access point. Number of APs is 4, the average SNR is S_0=10 dB, and the number of carrier reservation mini-slots used by sources is K=16, the number of RTS-CTS slots used by S-GeRaF is 10, the number of forwarding regions for S-GeRaF is 8, and the number of forwarding regions for GATOR and GATOR-GBRR is 32.

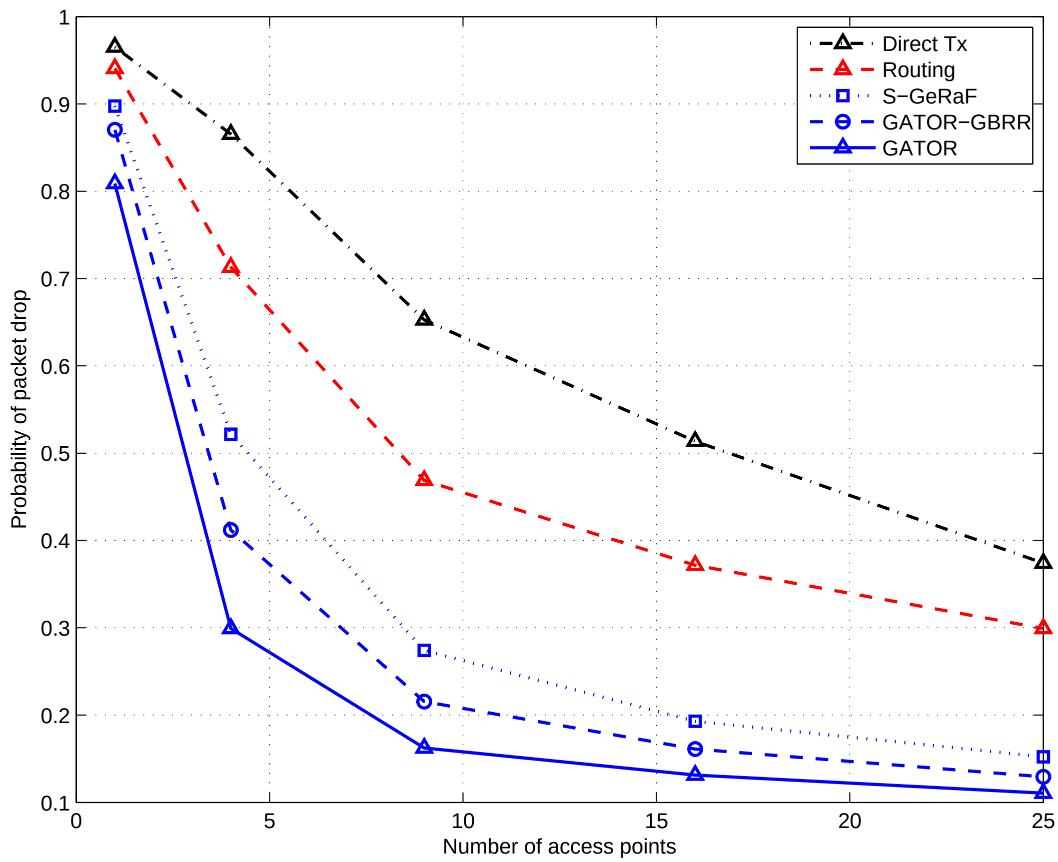


Fig. 8. Probability of packet drop from source reaching maximum number of transmissions ($N_{tx} = 4$) vs. number of access points. The average SNR is S_0=10 dB, and the number of carrier-reservation mini-slots used by sources is K=16, the number of RTS-CTS slots used by S-GeRaF is 10, the number of forwarding regions for S-GeRaF is 8, and the number of forwarding regions for GATOR and GATOR-GBRR is 32.

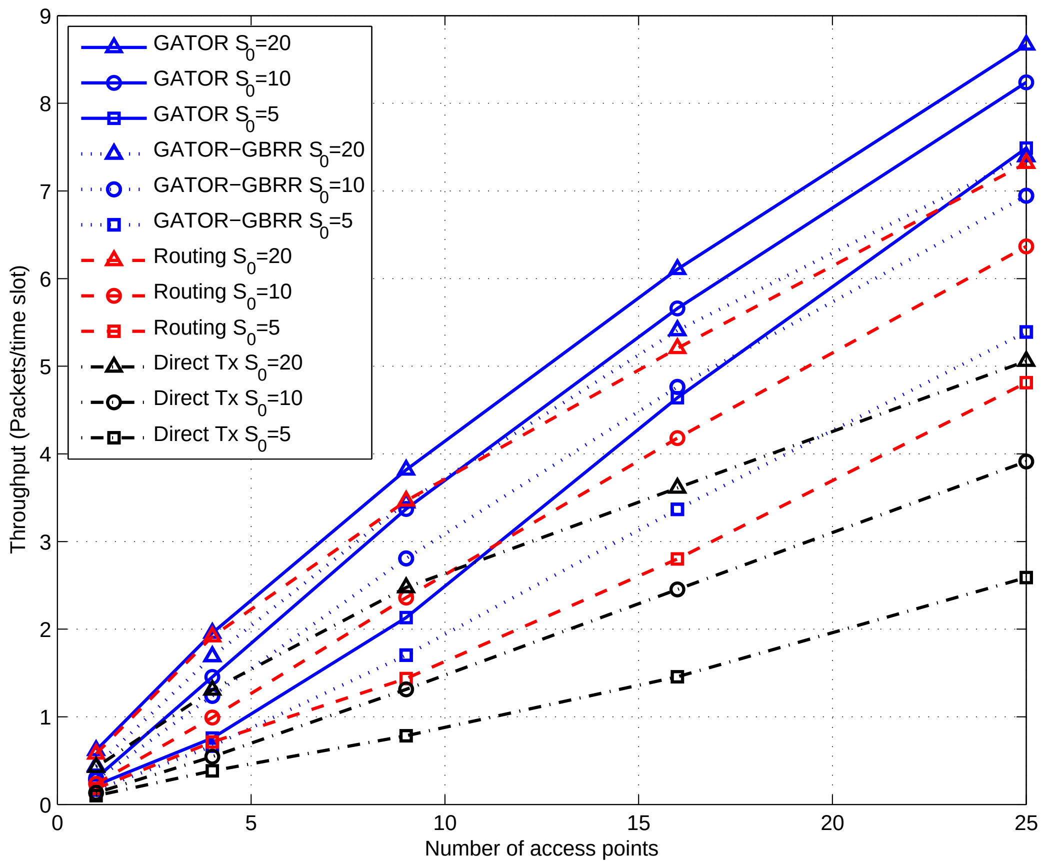


Fig. 9. Throughput vs. number of access points for different values of the average SNR S_0. The number of carrier-reservation mini-slots used by sources is K=16, and the number of forwarding regions for GATOR and GATOR-GBRR is M=32.

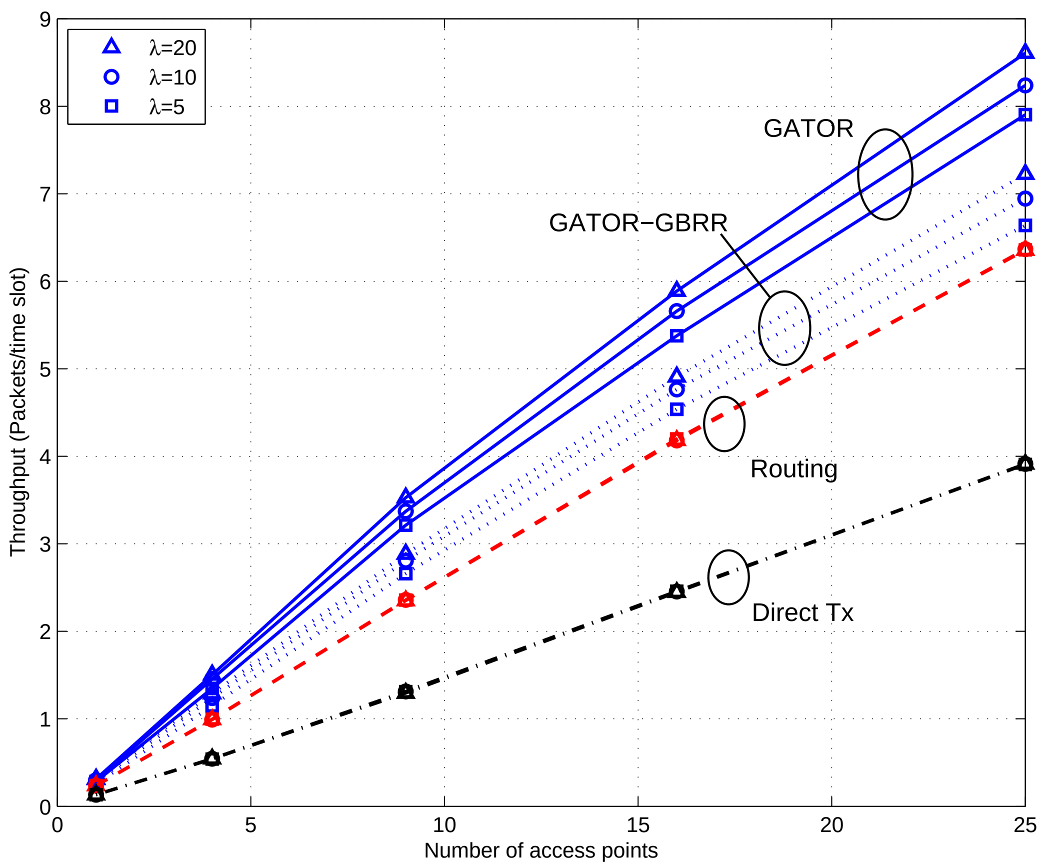


Fig. 10. Throughput vs. number of access points for different values of the density of on-nodes, λ. The average SNR is S_0=10 dB, the number of carrier-reservation mini-slots used by sources is K=16, and the number of forwarding regions for GATOR and GATOR-GBRR is M=32.

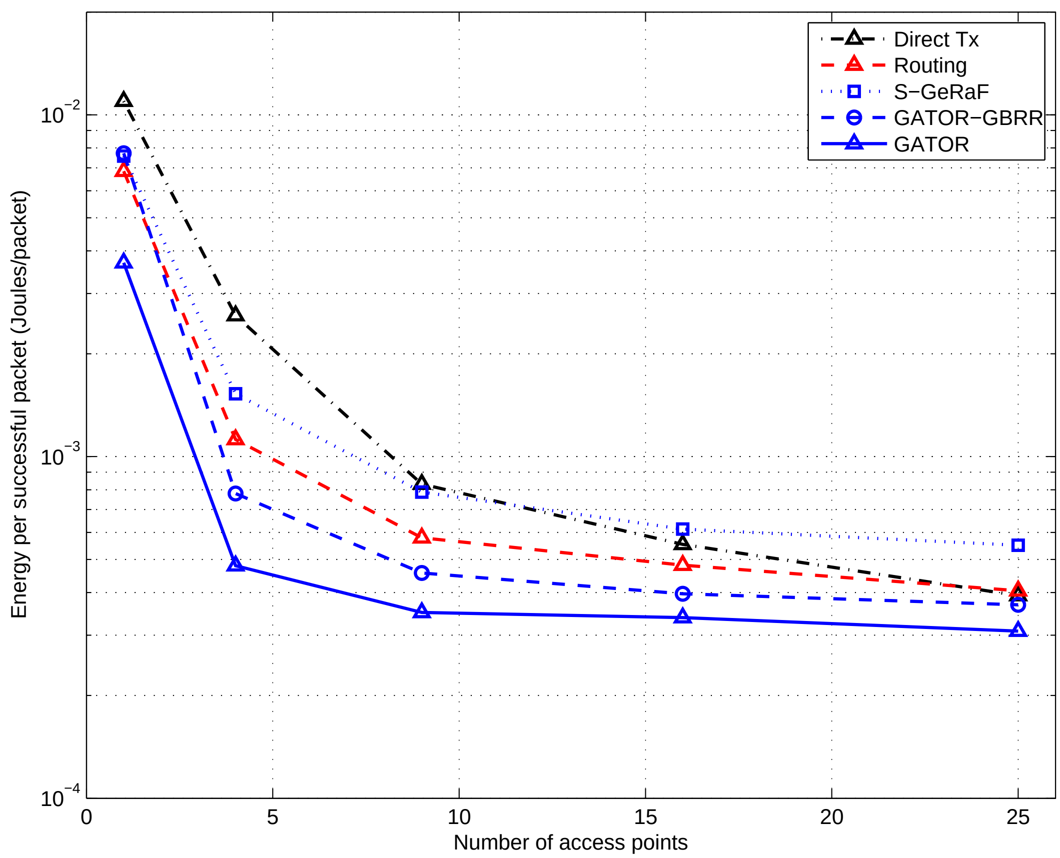


Fig. 11. Energy per successful packet, E_p, vs. number of access points. The average SNR is S_0=10, the number of carrier-reservation mini-slots for sources' transmission is K=16, the number of RTS-CTS slots used by S-GeRaF is 10, the number of forwarding regions for S-GeRaF is 8, and the number of forwarding regions for GATOR and GATOR-GBRR is 32.