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Abstract—In the reported metrics of the existing literature, the realistic wireless channel situation is generally ignored in selecting the appropriate next-hop relay node during packet forwarding in wireless sensor networks (WSNs). In this paper, we propose a new energy-efficient local metric, which is called the efficient advancement metric (EAM), for sensor networks. EAM considers both the maximum forwarding distance and the packet’s successful transmission probability by taking into account the wireless channel condition. This will enable the forwarding node to choose the most energy-efficient relay node in the geographic-informed routing protocol. Theoretically, we show the existence of the unique optimal relay node to maximize EAM over a typical Nakagami-$m$ channel of a code-division multiple-access (CDMA)-based WSN. Furthermore, based on the proposed metric EAM, we present a cross-layer packet-forwarding protocol channel-aware geographic-informed forwarding (CAGIF) by optimally selecting the relay nodes. CAGIF only requires that nodes have the knowledge of their own location information and the location information of the source and destination nodes. Numerical examples are presented to show the characteristics of EAM and the optimal distance. Compared with the previous geographic packet-forwarding schemes in WSNs, CAGIF consumes much lower energy and generates a significantly decreased signal overhead.

Index Terms—Energy efficiency, Nakagami-$m$-fading wireless channel model, packet forwarding, wireless sensor networks (WSNs).

I. INTRODUCTION

R ECENT advances in signal processing, microelectronics, embedded systems, and wireless communications have motivated the significant development of wireless sensor networks (WSNs). A WSN consists of a large number of sensors with sensing, data processing, communications, and networking capabilities. WSNs are characterized by dense node deployment and severe power, computation, and memory constraints. These unique characteristics pose challenges to the packet-forwarding design in WSNs.

In WSNs, geographic-information-based forwarding (GIF) is an efficient scheme for finding the appropriate next-hop relay node. Such a routing algorithm is able to utilize the location information while simultaneously avoiding a large number of control packets during route discovery. Existing papers usually choose the relay node based on a single criterion, i.e., the maximum advanced distance, to minimize the number of hops from the source to the destination node (e.g., [1] and [3]). However, the inherently unreliable wireless channel is generally ignored.

It is well known that the radio signal may experience serious fading during packet transmission [20], [21]. Consequently, the performance of traditional approaches may degrade substantially over a bad channel, which requires packet retransmission to ensure the correct packet reception and, hence, consumes more energy. Data dissemination in the deep-fading channel state consumes additional energy, and hence, it is advantageous to reduce the unnecessary retransmission due to the propagation impairment. An effective approach is to choose the next-hop relay node that is in good channel condition. This will offer efficient packet transmission and increase energy efficiency.

In this paper, our contributions include three folds to advance the state of the art in designing efficient packet-forwarding strategy in WSNs. First, we define a new energy-efficient local metric, termed as efficient advancement metric (EAM), which considers not only the forwarding distance but the energy efficiency of data transmission in a wireless channel situation as well. A finite-state Markov chain model is built for wireless channels to study the optimal distance of a relay node in a code-division multiple-access (CDMA)-based WSN. We prove that there exists a unique optimal forwarding distance to maximize EAM over the Nakagami-$m$ [31] channel model with a typical $m$. As a special case when $m = 1$, Nakagami-$m$ channel becomes a Rayleigh-fading channel. This indicates the existence of a unique optimal relay node over the Rayleigh-fading channel. Second, we propose an integrated cross-layer protocol channel-aware geographic-informed forwarding (CAGIF) that chooses the relay nodes from the links with favorable energy efficiency. In the proposed protocol, a forwarding node is able to choose the relay node with the maximum EAM. CAGIF only requires that nodes have the knowledge of their own location information and the location information of the source and destination nodes. Hence, no global topology information is required. This scheme is able to save energy and computing and storage space. In competing as the relay node, an opportunistic access mechanism is designed based on EAM. Third, extensive numerical examples are presented to investigate the characteristics of the optimal forwarding distance and EAM.
The performance of CAGIF is evaluated with respect to energy consumption and signaling overhead. The result indicates that CAGIF is able to substantially reduce the energy consumption and control signaling overhead compared to other geographic forwarding protocols.

II. RELATED WORK

Our study is motivated by geographic-information-based routing schemes and the impact of the realistic wireless channel conditions. Early work in geographic routing considered greedy forwarding [4] by utilizing the location information of nodes to forward data packets to the neighbor that is geographically closest to the destination. Greedy forwarding may fail when packets are routed to a node that has no neighbors closer to the destination node. Many recovery schemes, such as the face/perimeter routing techniques [5]–[7], have been presented to route around such voids to guarantee packet delivery in greedy forwarding. We, herein, set aside this issue for now and focus only on the approaches for improving the greedy forwarding aspect of geographic routing. More details about geographic-information-based routing schemes can be found in [8] and [9].

On the other hand, traditional geographic routing schemes, e.g., geographic random forwarding (GeRaF) [3], employ only location information to maximize the advanced distance with the aim of minimizing the number of hops from the source to the destination node. However, it assumes a highly reliable link, which is unlikely to be valid in realistic environments [11]. Recently, much research effort [16]–[19] has been dedicated in taking into account the realistic link condition. In [16], the expected transmission count (ETX) metric is used in a real testbed to minimize the total number of transmissions from the source to destination node, which, thus, decreases energy consumption. It is shown that paths with a smaller ETX perform better than those with shorter paths. In [17], energy-efficient forwarding strategies identify the weak link problem and make localized geographic forwarding decision by using the product of a packet reception ratio and the distance as the metric in a lossy environment. Biswas and Morris [18] reported the metric ExOR, which chooses the forwarding node with the lowest remaining cost to the destination. ExOR takes advantage of the choice of forwarders to provide throughput gains of a factor of two to four. Lee et al. [19] proposed the normalized advancement as the metric to select neighbors with the tradeoff between proximity and link cost. NADV-based routing schemes benefit greatly from fast and accurate link cost estimation. In contrast, our work studies a physically irregular sensor network in the presence of fading and theoretically verifies that there exists a unique optimal relay distance under a certain fading channel condition by using the introduced EAM.

With respect to the radio irregularity, Zorzi and Rao [21] examined an energy-efficient forwarding scheme to investigate the number of hops to reach a destination as a function of the density of available relay nodes in the presence of fading. Souryal et al. [22] investigated the information efficiency of channel-adaptive routing in a CDMA-based multihop network. A number of protocols have considered the problem of choosing forwarding hops based on channel conditions. The idea of selection diversity forwarding is presented in [12], where neighboring nodes that successfully receive the request-to-send (RTS) packet respond with clear-to-send (CTS) packets containing the signal-to-noise ratio (SNR) of the RTS, and the source node chooses a forwarder based on the reported RTS SNR. The candidate forwarding nodes are likely to send CTS frames simultaneously, potentially causing collisions. Jain and Das [13] improved it by letting the forwarders respond in a priority order specified in the initial RTS. Similarly, GeRaF [3] uses an RTS/CTS-based receiver contention scheme to select the best of many potential forwarders, which are prioritized based on geographic distance. Rossi and Zorzi [14] further improved GeRaF by considering the fading channel statistics and promoting a relay node with a small cost by ruling out the nodes that will likely lead to either unsatisfactory advancement or poor link quality. Different from their work, based on our conclusion that there exists a unique optimal relay distance under a certain fading channel condition, we employ an opportunistic access mechanism by utilizing EAM and sending reply messages after deferring an EAM-related time interval to reduce the collisions from the reply messages. Furthermore, based on EAM, we present an integrated cross-layer design to identify the optimal relay node. Rossi et al. [15] also studied the local selection of the next-hop node by maximizing the joint probability that a node wins the contention with a sufficiently low cost. Our work differs from that of Rossi et al. with respect to the access priority design, the relay node selection, and the transmission probabilities determination. It is noteworthy that our previous work [34] only investigates the achievable energy efficiency of a geographic-informed forwarding in a generic narrow-band WSN. In [35], only the numerical investigation is presented to examine the EAM characteristics without mathematical proofs.

The remainder of this paper is organized as follows. Section III introduces EAM, describes the system model, and provides EAM optimization. Section IV presents the CAGIF protocol with an opportunistic access scheme. Section V illustrates the numerical results in terms of EAM and the performance of CAGIF via extensive simulations. Section VI concludes the work.

III. EFFICIENT ADVANCEMENT METRIC

A. EAM Definition

In a geographic-informed forwarding algorithm, there is a predefined forwarding area to choose the relay node [23], [24]. All nodes with this forwarding area contend to be the possible next-hop relay node. In [24], various forwarding areas of contention-based geographic forwarding algorithms have been examined. In this paper, we denote $\phi$ as the radian forwarding area and employ polar coordinate $\left(R, \theta\right)$ as shown in Fig. 1, where $R$ denotes the distance between the source node and the relay node. We suppose that there is a line to connect the source node and the relay node. $\theta$ is the angle between this connection and the dashed line that connects the source node and the destination node. Let $R_f$ denote the distance between
the source node and the relay node due to the fading phenomenon. As shown in Fig. 1, the radian sector from $(R_f, -\phi/2)$ to $(R_f, \phi/2)$ is specified as the geographic region, where the relay nodes should reside.

Among the nodes that receive a packet and within the forwarding area, the node that achieves the maximum advancement toward the destination node should be the one forwarding the packet. However, the transmission in a deep-fading channel state may incur more retransmissions and, hence, result in higher energy consumption. Consequently, geographically-informed forwarding algorithm requires a metric that reflects the successful advancement from any node to the destination. Moreover, the algorithm shall consider both the forwarding advancement and the energy efficiency of data transmission. To satisfy such requirements, the inherently varying channel conditions should be taken into account in the physical layer. Additionally, adaptive transmission needs to be considered in the medium access control (MAC) layer.

We define $EAM$ as the product of the following two items: 1) the projection of the distance between the source node and the relay node to the line connecting the source node and the destination node and 2) the probability of successful packet transmission $P_s$, i.e.,

$$EAM = R \cdot \cos \theta \cdot P_s$$ \hspace{1cm} (1)

where $P_s$ will be given in Section III-B.

In the proposed channel-aware forwarding scheme CAGIF, a relay node should be chosen to satisfy

$$\mathcal{R} = \arg \{R, \theta, A\} \max \{R \cdot \cos \theta \cdot P_s\}$$ \hspace{1cm} (2)

where $A$ is the channel fading amplitude. That is, the CAGIF algorithm chooses the next-hop relay node within the forwarding area that can maximize the forwarding progress and that can also be in a good channel condition. In this case, we need not define an energy cost function since the relay node selection is not based on any energy criterion but EAM. The reduced energy consumption is mainly due to the optimal relay node selection. Based on the instantaneous channel condition, a larger transmission range is allowed to achieve a greater advancement toward the destination, thereby reducing the number of hops to the destination. On the other hand, the increased transmission range will lead to higher multiple access interference (MAI). This will decrease the probability of successful packet transmission and, hence, will result in lower energy efficiency. In Section III-E, we will theoretically prove the existence of optimal forwarding distance to achieve the maximum advancement with acceptable MAI.

**B. System Model**

Let us consider a wireless CDMA multihop network that operates under heavy traffic conditions, where nodes are randomly distributed in the plane according to a 2-D Poisson point process with average density $\lambda$. Then, the probability of finding $k$ nodes within the circular region with radius $a$ is

$$e^{-\lambda \pi a^2} \left(\frac{\lambda \pi a^2}{k!}\right)^k.$$  

The system is time slotted, and each node transmits data independently with transmission probability $p$ in each slot.

We assume that the system operates in an asynchronous direct-sequence scheme of binary phase-shift keying with a rectangular chip pulse, and that nodes transmit at the same transmission power. Following [2] and [25], the signal-to-interference-plus-noise ratio (SINR) $M$ is represented as

$$M = \left(\frac{2Y}{3GP_r} + \frac{1}{\mu_0}\right)^{-1}$$ \hspace{1cm} (3)

where $P_r$ is the received signal power, $Y$ is the total interference power, $G$ is the processing gain, and $\mu_0$ is the SINR at the receiver in the absence of MAI. The total MAI signal $Y$ is assumed to be well approximated by a Gaussian random variable [2], [37]. Let $f_M(\cdot)$ and $F_M(\cdot)$ denote the probability density function (pdf) and the cumulative distribution function (cdf) of the random variable $M$, respectively.

Depending on the fading status of the channel and the distance between the transmitter–receiver pair, there are different receiving signal strengths and, thus, different SINRs. Let $\mu_t$ denote the threshold value of the SINR for successful packet reception. Note that the probability of packet success is dependent on the coding scheme. According to [2], for the best low code, the packet success probability approaches a step function at a certain value of $\mu_t$. Let $p_M(\cdot)$ denote the step function for the packet success probability

$$p_M(\mu) = \begin{cases} 1, & \mu \geq \mu_t \\ 0, & \mu < \mu_t \end{cases}$$ \hspace{1cm} (4)

Based on the expression of the step function, $P_s$ is developed as

$$P_s = \int_0^\infty p_M(\mu) f_M(\mu) d\mu = \int_0^\infty p_M(\mu) (1 - F_M(\mu)) d\mu = 1 - F_M(\mu_t).$$ \hspace{1cm} (5)

A complex channel model that considers both large-scale path loss and multipath fading is used. We use a generic Nakagami-$m$-fading distribution to characterize the multipath fading since...
it is a two-parameter distribution with the Nakagami-fading parameter \( m \) and the average received power parameter \( \Omega \), and it can give the best fit to the statistics of signals transmitted over multipath channels in land-mobile and indoor-mobile environments by adaptively adjusting the values of the \( m \) parameter. We consider the slowly varying flat fading, and hence, the channel remains roughly constant over a time slot. Let \( P_t \) denote the transmission power. Then, the received signal power \( P_r \) is given by

\[
P_r = \frac{A^2 P_t}{P^0}
\]

(6)

where \( n \) denotes the path loss exponent. The channel fading amplitude \( A \) is a Nakagami-fading random variable with a pdf given by [31]

\[
f_A(\alpha) = 2 \left( \frac{m}{\Omega} \right)^m \frac{\alpha^{2m-1}}{\Gamma(m)} e^{-\frac{m\alpha^2}{\Omega}}, \quad \alpha \geq 0
\]

(7)

where \( m \geq 1/2 \), and \( \Gamma(\cdot) \) is the gamma function defined by

\[
\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt, \quad z \geq 0.
\]

The parameter \( m \) characterizes the fading severity. As \( m \) increases, the fading becomes less severe. It is well known for the special case of \( m = 1 \), the Nakagami-\( m \) distribution represents the Rayleigh distribution. The case \( m = 1/2 \) gives the one-side Gaussian fading, which is the fading in the worst case. Moreover, the Nakagami-\( m \) distribution can approximate Rice and log-normal distribution when \( m > 1 \) [32].

C. MAI Power Distribution in a Nakagami-\( m \)-Fading Channel

In [33], we generalize the fading channel model and derive the distribution of MAI power under a generic Nakagami-\( m \)-fading channel model. The cdf of interference \( Y \) is expressed as

\[
F_Y(y) = \begin{cases} 
\text{erfc} \left( \frac{\lambda_l \sigma^2}{2\sqrt{2y}} \right), & m = 1 \\
\text{erfc} \left( \frac{2\lambda_l \alpha \sigma^2}{\sqrt{2y}} \right), & m = 2 \\
\text{erfc} \left( \frac{3\lambda_l \alpha^2 \sigma^2}{16\sqrt{2y}} \right), & m = 3 \\
\text{erfc} \left( \frac{3\lambda_l \alpha^2 \sigma^2}{64\sqrt{2y}} \right), & m = 4 
\end{cases}
\]

(8)

for \( y > 0 \), where \( \lambda_l = \lambda P_t \), and \( \sigma \) is a fading parameter. We have set the path loss exponent to a typical value \( n = 4 \), which can also give the closed-form expression of density according to [2].

D. Markov Model for Nakagami-\( m \)-Fading Channels

The wireless channel is modeled by constructing a finite-state Markov chain [27], [28]. We formulate the \( Q \)-state Markov model by partitioning the range of the channel fading amplitude \( \alpha \) into \( Q \) intervals, where \( Q \) is the partitioned number of channel conditions of a Nakagami-\( m \)-fading channel. Let \( q \) \( (q = 1, \ldots, Q) \) denote the different channel states. A higher \( q \) represents a better channel condition. Fig. 2 shows the pdf of a Nakagami-\( m \)-fading channel with respect to the channel fading amplitude. Let \( \alpha_q^l \) and \( \alpha_q^u \), respectively, denote the lower and upper threshold of \( \alpha \) for the \( q \)-th \( (q = 1, \ldots, Q) \) channel state interval.

The steady-state probability of the \( q \)-th channel state is given by

\[
Pr[\alpha_q^l < \alpha \leq \alpha_q^u] = \int_{\alpha_q^l}^{\alpha_q^u} f_\alpha(\alpha) d\alpha
\]

\[
= \left( \Gamma \left( \frac{m \alpha_q^u^2}{\Omega} \right) - \Gamma \left( \frac{m \alpha_q^l^2}{\Omega} \right) \right) / \Gamma(m).
\]

(9)

Without loss of generality, we employ equally probable partitioning [26], i.e., we find a set of thresholds

\[
Pr[\alpha_q^l < \alpha \leq \alpha_q^u] = \frac{1}{Q}.
\]

(10)

For practical performance evaluation, covering 99.99% of the pdf values is sufficient. We can then obtain \( \alpha_q^l = 0 \) and \( \alpha_Q^u = 3 \).

E. EAM Derivation

By substituting (3) into (8), we obtain the conditional cdf of SINR on the channel fading amplitude \( \alpha \) as

\[
F_M(\mu | \alpha) = \begin{cases} 
1 - F_Y \left[ \frac{3G}{2\mu_0} \left( \frac{\alpha^2}{\mu} - \frac{1}{\mu_0} \right) \right], & \mu < \alpha^2 \mu_0 \\
1, & \mu \geq \alpha^2 \mu_0.
\end{cases}
\]

(11)

Define the multiple access capability as [37]

\[
K(\mu, \alpha) = \frac{3G}{2} \left( \frac{\alpha^2}{\mu} - \frac{1}{\mu_0} \right).
\]

(12)

It can be interpreted as a measure of the number of tolerable interferers for a certain required SINR \( \mu \) at a receiver with
signal fading amplitude $\alpha$. Thus, we can obtain

$$F_M(\mu) = \int_0^\infty F_{M/A}(\mu | \alpha) f_A(\alpha) d\alpha$$

$$= \int_0^\infty f_A(\alpha) d\alpha$$

$$+ \int_0^\infty \left( 1 - F_Y \left[ \frac{1}{R^4} K(\mu, \alpha) \right] \right) f_A(\alpha) d\alpha$$

$$= 1 - \sum_{q=1}^Q \alpha_q^u \cdot F_Y \left[ \frac{1}{R^4} K(\mu, \alpha) \right] f_A(\alpha) d\alpha$$

(13)

where $\alpha_q^u = \alpha_{q+1}^u$. Note that $\alpha_q^u = \max\{\alpha_q^l, \sqrt{\mu/\mu_0}\}$.

As a result, EAM can be expressed as

$$R \cdot \cos \theta \cdot P_s = R \cdot \cos \theta \cdot (1 - F_M(\mu_t))$$

$$= R \cdot \cos \theta \cdot \sum_{q=1}^Q \alpha_q^u \cdot F_Y \left[ \frac{1}{R^4} K(\mu, \alpha) \right] f_A(\alpha) d\alpha.$$  

(14)

Therefore, the adaptation mechanism can be defined as

$$\arg\left| R \cdot \cos \theta \cdot P_s \right|_{\alpha_q^u} = \max\left\{ R \cdot \cos \theta \cdot \int_{\alpha_q^u}^{\alpha_q^l} F_Y \left[ \frac{1}{R^4} K(\mu_t, \alpha) \right] f_A(\alpha) d\alpha \right\}$$

(15)

where $R_q$ and $A_q$ denote the particular results of the variables $R$ and $A$ in the $q$th channel state. Let us define

$$(R \cdot \cos \theta \cdot P_s)_q = R \cdot \cos \theta \cdot \int_{\alpha_q^u}^{\alpha_q^l} F_Y \left[ \frac{1}{R^4} K(\mu_t, \alpha) \right] f_A(\alpha) d\alpha.$$  

(16)

In the Appendix, we prove that the equation above is a concave function in terms of the variable $R$ over Nakagami-$m$ with a typical $m$. Hence, there exists a unique optimal value to maximize $(R \cdot \cos \theta \cdot P_s)_q$. Thereafter, we can numerically find the optimum value of $R$ for each channel state to maximize $R \cdot \cos \theta \cdot P_s$ in (15) such that a transmitter can choose an optimal relay node to achieve the maximum EAM.

IV. CAGIF Protocol

As explained, EAM offers a cross-layer design by effectively integrating the optimal selection of the relay node, the energy efficiency, and the underlying channel situations. Based on this, we will develop an integrated physical/MAC/routing protocol of CAGIF. CAGIF only requires that nodes have the knowledge of their own location information and the location information of the source and destination nodes. This way, no global topology information is required. This will save storage space and reduce the signaling overhead in the routing updating procedure.

Before delving into the protocol design detail in CAGIF, we first present the motivations and basic principle. When a specific node has data to transmit, it will send out the probing signal, including its own and the destination node location information. Upon hearing the probing signal, all nodes in the forwarding area will compete to be the relay node. To avoid collision, each node has the appropriate channel access priority, which is determined by EAM. Due to the EAM characteristics, the criteria of selecting an appropriate relay node involve the direct successful advancement toward the destination node. To enable CAGIF, nodes can vary the transmission range to search for the optimal relay node on the basis of EAM. A forwarding node is able to select the locally optimal next-hop node. Following the similar procedure, whenever a node receives a packet, it will favor the next-hop node that is closer to the destination and will maximize EAM as well. This will progressively forward the packet toward the target region.

The wireless channel is divided into the control channel and the data channel. Through the control channel, all nodes are able to operate in a time-slotted mode and are synchronized. CAGIF consists of the following three phases: 1) probing phase; 2) relay node determination phase; and 3) data transmission phase. The first two stages are implemented in the control channel, whereas the last stage is transmitted over the data channel.

A. Opportunistic Channel Access in CAGIF

In case a source node has data to transmit, it will send out the probing signal of request (REQ) via the control channel. The message REQ indicates the source identifier (ID), the destination node ID, and their location information. For those nodes in the forwarding area, and upon hearing the REQ, they will compete to be the relay node.

During the competition, to prioritize the nodes in better channel situations, we partition the nodes in the forwarding area into different access priorities. We suppose that the wireless channel is partitioned into $Q$ states. Let $\text{EAM}_{\max,q}$ denote the maximum EAM in the channel state $q$ ($1 \leq q \leq Q$). We define a node’s access priority as $i$ if a node’s EAM value is greater than $\text{EAM}_{\max,q-i, Q-i+1}$, and less than or equal to $\text{EAM}_{\max,q-i+1}$, i.e.,

$$\text{EAM}_{\max,q-i} < \text{EAM} \leq \text{EAM}_{\max,q-i+1}.$$  

(17)

Nodes have the same access priority $i$ if their EAM satisfies the inequality above.

Upon receiving the message REQ, each node will respond with a reply (REP) packet after deferring a time duration $T_i$ ($i = 1, 2, \ldots, Q$). Here, the deferred period $T_i$ varies in
different classes of access priority and is able to reflect the channel access priority in acting as the relay node. We refer to it as opportunistic channel access in CAGIF. Specifically, the deferred duration $T_i$ is calculated as

$$T_i = T_{L,i} + T_{U,i}^{\prime}, \quad 1 \leq i \leq Q$$

(18)

where $T_{L,i}$ represents the minimal deferring threshold in the $i$th access priority. $T_{U,i}^{\prime}$ denotes the deferring value and is randomly selected from $[0, T_{U,i}]$, with $T_{U,i}$ being the upper bound of $T_{U,i}^{\prime}$. Thus, $T_{L,i}$ and $T_{U,i}$ are, respectively, given by

$$T_{L,i} = \begin{cases} 0, & i = 1 \\ T_{U,i-1}, & 2 \leq i \leq Q \end{cases}$$

(19)

$$T_{U,i} = \omega \pi (R_{i,2}^2 - R_{i,1}^2)$$

(20)

where $R_{i,1}$ and $R_{i,2}$, respectively, represent the lower and upper bound of the relay node distance in the $i$th access priority. Accordingly, the value of $R_{i,1}$ and $R_{i,2}$ can be obtained by equalizing the EAM when $q = Q$ with the maximum EAM in case $q = Q - i$, i.e.,

$$(R_{i,j} \cdot \cos \theta \cdot P_s)_{q=Q} = \begin{cases} \text{EAM}_{\text{max}, Q-i}, & i < Q \\ 0, & i = Q \end{cases}$$

(21)

for $j = 1$ or $2$, with $R_{i,1} < R_{i,2}$. Fig. 3 shows an example to illustrate $R_{i,1}$ and $R_{i,2}$ in case $Q = 3$. $R_{i,1}$ and $R_{i,2}$ are, respectively, the smallest and largest relay node distance in the first access priority. $R_{2,1}$ and $R_{2,2}$ are, respectively, the smallest and largest relay node distance in the second access priority.

The predefined parameter $\omega$ is equal to the product of the node distribution density $\rho$ and control packet transmission time $\tau$, i.e., $\omega = \rho \tau$. According to the ratio of the scanned area of a node’s EAM over the coverage area of the EAM in its access priority, we define

$$T_{U,i}^{\prime} = T_{U,i} \frac{\text{EAM}_{\text{max}, Q+1-i} - R \cdot \cos \theta \cdot P_s}{\text{EAM}_{\text{max}, Q+1-i} - \text{EAM}_{\text{max}, Q-i}}$$

(22)

This indicates that a node with a larger EAM defers a shorter duration for the competition and, hence, has a higher opportunity in winning the competition. Consequently, nodes within different priority regions adopt different deferring values $T_{L,i}$; nodes within the same priority region defer the random value between $[0, T_{U,i}]$. Following this, all nodes in the forwarding area have different deferring values to compete as the relay node. This alternatively indicates the node priority to transmit REP. Lower priority nodes defer a longer period while higher priority nodes defer a shorter time duration. It is clear that such an opportunistic access mechanism has the advantage of efficiently saving energy by reducing the unnecessary packet contention.

On the other hand, the REP packet may specify the duration of a node to be a relay candidate within its current priority region, which is estimated by its instantaneous and past channel conditions. In this paper, without loss of generality, we set the update interval to 1 s in simulation. After the successful REQ/REP handshaking, the sender picks the optimal relay node and initiates the data transmission over the data channel. During the contention, the collisions may occur when more than one node reply to the REQ or when no reply can be received. In such a case, the source node will retransmit an REQ message until the sender receives the REP message successfully.

B. Implementation Issue

The selection of the optimal relay node in CAGIF is based on the knowledge of EAM, which is acquired through the estimation of the advanced distance and the channel states. The location information can be obtained through positioning devices, e.g., GPS [10]. It has been verified that the introduction of GPS is able to significantly reduce the communication costs incurred by path discovery and update messages in maintaining routing tables. In such a case, the positioning energy consumption introduced by GPS is almost ignorable in comparison with the energy consumption for a large number of communication overheads in routing maintenance (see [3], [14], [15], and [17], and the references therein). Then, the distance estimation may be achieved according to the piggybacked location information in the control messages (REQ). On the other hand, the estimation of the channel states is achieved by comparing the measured signal attenuation to a set of channel gain thresholds in a control channel. Based on the information, nodes could have the knowledge of EAM.

V. PERFORMANCE EVALUATION

A. EAM Characteristics

With reference to a direct-sequence mobile packet radio network [29], [30], we choose the system parameters $\mu_t = 6.6$ dB (required BER $= 10^{-5}$ and cyclic redundancy correction code gain $= 1$ dB), $\mu_0 = 26.6$ dB, and $\lambda = 10^{-3}$. The parameter $\sigma$ is set to be $1/\sqrt{2}$, and hence, we have $\Omega = 2\sigma^2 = 1$. The thresholds for the partitioned channel state intervals are illustrated in Table I, where we replace $\alpha_1 = 0$ with $\alpha_1 = \sqrt{\mu_t/\mu_0} = 0.1$, as noted in (13). Thereafter, we specify $\theta = 0$ to focus on the
TABLE I

<table>
<thead>
<tr>
<th>( m )</th>
<th>( Q )</th>
<th>( \alpha_1 )</th>
<th>( \alpha_1^* )</th>
<th>( \alpha_2 )</th>
<th>( \alpha_2^* )</th>
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Fig. 4. EAM versus the distance of a relay node with varying values of the spreading factor \( G \) for different channel conditions of a Rayleigh-fading channel (\( m = 1, Q = 2, \) and \( p = 0.3 \)).

study of the optimum distance of a relay node that corresponds to a certain channel condition.

Fig. 4 shows EAM in terms of the distance of a relay node with varying values of the spreading factor \( G \) for different channel conditions of the Rayleigh-fading channel. The curves indicate an optimum value of \( R \) to maximize the EAM for each partitioned channel state \( q \). We observe that \( q = 2 \) gains a substantially higher EAM value over \( q = 1 \). This is because a higher \( q \) value indicates a better channel condition and, hence, achieves a higher packet successful transmission probability. With increasing spreading factor \( G \), there is better EAM. Moreover, the optimal distance of the relay node increases with a higher \( G \) value. This is attributed to the increasing multiple access capability with a larger spreading factor. In the following, if not specified, \( G \) is set to 64 to investigate the performance of the EAM.

Fig. 5(a)–(c) shows EAM in terms of the relay node distance over a Rayleigh-fading channel with different numbers of partitioned channel states. For the packet successful transmission probability under the various channel conditions, there is an optimum distance of a relay node to maximize EAM. With more channel state partitions, the optimum distance becomes longer due to better instantaneous channel states. However, the increasing slope becomes smaller due to the fact that more channel partitions approach the perfect estimation of the instantaneous channel state. For instance, the optimum distance becomes larger from 48 to 52 to 54 with increasing \( Q \), i.e., when \( Q = 2, Q = 3, \) and \( Q = 4 \).

Fig. 6(a)–(c) shows EAM in terms of the relay node distance with different channel models. For a different \( m \), there is a different optimum relay node to maximize EAM. In addition, the optimum distance increases with a larger \( q \), which is in accordance with the observation in Fig. 5.

Fig. 7 shows the optimum distance of a relay node in terms of the average transmission probability over a Rayleigh-fading channel with a different node density. As the packet transmission probability \( p \) increases, the optimum distance of the relay node decreases. For a fixed transmission probability, the optimum distance decreases with a higher node density. This is due to more MAI with an increasing number of nodes and, hence, more failed packet transmissions.

B. CAGIF Performance Evaluation

In this section, we will evaluate the performance of the proposed CAGIF with respect to energy consumption and control overhead under different channel conditions. A discrete-event simulation program in C++ is developed. The average total energy consumption per packet is calculated by doing the average summarization of the transmission power per packet over a routing path. The average signaling overhead is calculated based on the number of associated control messages transmitted per packet that are successfully delivered from the source to the destination node. We consider a WSN where the sensor nodes are randomly and uniformly distributed in a square area of 500 m × 500 m, with density \( \lambda \). The propagation channel model is as what we have described in Section III, and the path loss factor is set to 4, corresponding to the closed-form pdf derivation of MAI in a Nakagami-\( m \)-fading channel model. The channel rate is 2 Mb/s, with a control channel rate of 0.3 Mb/s. The traffic type is constant-bit-rate user datagram protocol with a packet size of 512 bytes. We assume that all the control packets are of the same length of 50 bytes. Accordingly, we have \( \tau = 0.00133 \) s. The simulation time is 1000 s. We randomly choose a node as the destination node and choose ten nodes as the source nodes, with the distance between the source node and destination node set to 300 m. Each source node has a traffic flow to transmit data to the destination node. Our proposed CAGIF protocol is employed to determine the optimal routing path for packets from a source node to the destination node. We then calculate the average value of energy consumption over these ten source–destination paths.

In this paper, we focus on the study of an optimum forwarding distance to improve the energy efficiency and intend to show the protocol design difference between our scheme and the previous schemes that employ a fixed transmission range. If not specified, we choose the transmission power \( P_t = 20 \) mW when the transmission range is 40 m. For the sake of illustration, we follow the similar implementation in GeRaF [3] and simulate the GIF scheme, where a forwarding node is chosen in case this node is the closest one to the destination in the forwarding region. Note that a slightly different point is that the same forwarding area as that of CAGIF is used in our simulations. For a node that has data to transmit, it broadcasts...
an REQ message over the control channel. All nodes in its forwarding area determine their own priority region according to their distance from the sender. The nodes in the higher priority region, i.e., closest to the destination node, contend first to be the relay nodes by sending back REP messages. The nodes in the same priority region randomly send REP messages. If not specified, in the following, we choose the number of partitioned priority regions $N_p = 3$. An automatic repeat request is employed to ensure the successful packet reception when the packet transmission fails.

Fig. 8(a)–(c) shows the average total energy consumption per packet, with a 95% confidence interval in terms of the average density with different $m$’s in a Nakagami-$m$-fading channel. In this example, $G = 64$, $Q = 3$, and $p = 0.3$. The energy consumption in all schemes decreases with the heavier node density. This is due to the higher possibility of finding the optimal relay node with an increased node density. The comparison indicates that the power consumption is reduced with a larger $m$ in a Nakagami-$m$-fading channel. With a larger $m$, a node will experience less-severe fading. For any $m$, CAGIF achieves much lower power consumption compared with the GIF scheme. This can be explained with different policies in selecting the relay node. In CAGIF, the relay node can approximate the optimal one since it applies EAM that is able to maximize the efficient forward progress and, henceforth, reduces the number of retransmissions. In contrast, in GIF, although different priority regions are partitioned, nodes in the same priority region contend randomly without considering the underlying channel situation, which cannot identify a better candidate relay node. When the sensor network density is not very heavy, e.g., $0.001 \leq \lambda \leq 0.004$, energy consumption is significantly saved. With an even higher node density, the energy reduction is insignificant. In such a case, the relay node approaches the optimum value. Moreover, the confidence interval of CAGIF is much smaller than those of GIFs, which is an additional advantage that stabilizes the network performance.
Fig. 8. Average total energy consumption versus the node density with different $m$'s ($G = 64, Q = 3$, and $p = 0.3$). (a) $m = 1$. (b) $m = 2$. (c) $m = 4$.

Fig. 9 shows the average total energy consumption in terms of the average transmission probability in a Rayleigh-fading channel ($G = 64, Q = 3$, and $\lambda = 0.003$). It is observed that the energy consumption in CAGIF decreases with a heavier transmission probability $p$. With a larger $p$, the limited multiple-access capability under a high traffic load results in a smaller optimum distance of a relay node to maximize $EAM$. Although the number of hops may become larger due to the shorter optimum distance, the transmission power reduction dominates the total energy consumption. This achieves the final decreased power consumption. In contrast, in GIF, the transmission power remains constant regardless of any channel situation. The packet successful transmission probability $P_s$ reduces with a greater traffic load. Consequently, the number of packet retransmission increases, which leads to higher energy consumption. GIF with $R = 60$ performs worse than GIF with $R = 40$. A larger transmission range $R$ indicates more MAI and, thereby, incurs more packet retransmissions to ensure successful packet reception.

Fig. 10 shows the control overhead in terms of the node density over a Rayleigh-fading channel ($G = 64, Q = 3$, and $p = 0.3$). The nodes in the same geographical region have the same priority. This causes a serious collision and generates a substantial control overhead. With the higher node density $\lambda$, the performance of control overhead degrades significantly. Furthermore, with the larger transmission range, more nodes participate in the contention and lead to the even higher control overhead. Different from GIF, the REP messages are transmitted on the basis of the new metric in CAGIF. Another attractive property is that the performance gain of CAGIF becomes larger with more nodes. This demonstrates the scalability advantage of CAGIF. It is noteworthy that there is a special case. The overhead in CAGIF is slightly higher than that in GIF, with $R = 40$ when $\lambda \leq 0.0017$. This can be explained as follows. The optimum transmission range is larger than 40 in CAGIF for the low density, which incurs more contenders in CAGIF and, hence, results in a slightly increased overhead.

We have shown that CAGIF performs well in static networks and now investigate how well they work when confronted with mobility. We study a scenario where the source and destination nodes are static and 10% of the remaining nodes move according to the random way-point mobility model [38]. The speed is randomly chosen between 1 and 10 m/s. The pause time varies to observe the impact of different degrees of node mobility. Fig. 11 shows the average total energy consumption with a
VI. CONCLUSION AND FUTURE WORK

In this paper, a new local energy-efficient metric of EAM has been proposed for CAGIF in WSNs. This metric explores the optimal selection of a relay node by adjusting the transmission ranges according to the underlying channel conditions, which, hence, presents a cross-layer combination by effectively integrating routing and MAC, as well as physical layer in a geographic-informed WSN. An analytical framework has been provided, and numerical results have shown that there exists a unique optimum distance of a relay node under a certain channel condition to maximize the EAM for any fading conditions of a CDMA-based WSN. Compared with the previous GIF schemes in WSN, the CAGIF protocol is able to achieve low energy consumption and incurs the least control message overhead as well. An interesting future topic is the further investigation of the metric EAM or the protocol CAGIF by considering different energy consumption levels during different sensor states.

APPENDIX

In this Appendix, we will prove that there exists an optimal value $R_\alpha$ to achieve maximum EAM in a Nakagami-$m$ channel with a typical $m$. In such a case, the function $F_Y(y)$ in (8) can be generically expressed as

$$F_Y(y) = \text{erfc} \left( \frac{A_m}{\sqrt{K}} \right)$$

where the parameter $A_m$ varies with different $m$'s.

Without loss of generality, we remove unrelated variables and rewrite (16) with generic upper range $b$ and lower range $a$ in the integral. Let

$$g(R) = R \int_a^b F_Y \left( \frac{K(\mu_\alpha, \alpha)}{R^4} \right) f_A(\alpha) d\alpha$$

$$= R \int_a^b \text{erfc}(A_\alpha R^2) f_A(\alpha) d\alpha$$

(24)

where $A_\alpha = A_m/\sqrt{K(\mu_\alpha, \alpha)}$. Next, we need to show that there exists an optimal distance to achieve maximum EAM based on the equation above. Referring to the formula for the first-order derivative of complementary error function $\text{erfc}(z)$ [36], we have

$$\frac{d}{dz} \left( \text{erfc}(z) \right) = -\frac{2e^{-z^2}}{\sqrt{\pi}}$$

and taking the first-order derivative operation on (24), we have

$$g'(R) = \int_a^b \left[ \text{erfc}(A_\alpha R^2) - \frac{4A_\alpha R^2 e^{-A_\alpha^2 R^4}}{\sqrt{\pi}} \right] f_A(\alpha) d\alpha.$$  

(25)

Here, we have

$$\lim_{R \to 0} g'(R) > 0 \quad \lim_{R \to +\infty} g'(R) < 0.$$  

(26)

This means that $g(R)$ increases when $R$ approaches zero and decreases when $R$ approaches positive infinite. Hence, there is a maximum point of $g(R)$.

Next, we further show that there is only one maximum point and the second-order derivative is less than zero at this point. This makes the local maximum point of $g(R)$ a unique maximum point. We set (25) to zero. Then, we have

$$\text{erfc}(A_\alpha R^2) = \frac{4A_\alpha R^2 e^{-A_\alpha^2 R^4}}{\sqrt{\pi}}.$$  

Let $x = A_\alpha R^2$. Then, we have the following alternative function:

$$\text{erfc}(x) = \frac{4xe^{-x^2}}{\sqrt{\pi}}.$$  

After we analyze the characteristics of the two sides of the function above, the equation has a single zero point, which is denoted as $R_\alpha$.

Since the function $\text{erfc}(z)$ is bounded by [36]

$$\text{erfc}(z) \leq \frac{2}{\sqrt{\pi}} \frac{e^{-z^2}}{z + \sqrt{z^2 + \frac{1}{4}}}$$  

(27)

95% confidence interval with respect to the pause time over the Rayleigh-fading channel. In this example, $G = 64$, $Q = 3$, $\lambda = 0.003$, and $p = 0.3$. The comparison indicates that CAGIF consumes lower energy than GIF. In addition, the increase in energy consumption is minimal, even with the highest mobility. Consequently, CAGIF works well with node mobility, and energy consumption is minimal, even with the highest mobility. In addition, the increase in energy consumption is minimal, even with the highest mobility.
we have
\[
\frac{4A_o R_o^2 e^{-A_o R_o^4}}{\sqrt{\pi}} = \text{erfc} \left( A_o R_o^2 \right)
\]

(27)

After simplifying this equation, we obtain the following inequality expression:

\[
R_o^4 \leq \frac{1}{(16/\pi + 4)A_o^2}
\]

(29)

Furthermore, taking the second-order derivative operation on (24), we have

\[
g''(R) = \int_a^b \frac{4A_o R_o e^{-A_o R_o^4}}{\sqrt{\pi}} \left[ 4A_o^2 R_o^4 - 3 \right] f_A(\alpha) d\alpha.
\]

(30)

Based on this result, we have

\[
\frac{4A_o R_o e^{-A_o R_o^4}}{\sqrt{\pi}} \left[ 4A_o^2 R_o^4 - 3 \right] \leq \frac{4A_o R_o e^{-A_o R_o^4}}{\sqrt{\pi}} \left[ \frac{4}{(16/\pi + 4)} - 3 \right] < 0.
\]

(31)

This shows that the second-order derivative at point $R_o$ is less than zero. It is summarized that (24) is twice differentiable, i.e., the second-order derivative is less than zero at the zero point of the first-order derivative function. Hence, there exists an optimal distance to achieve maximum EAM. In addition, there is a single maximum point that, consequently, is the unique maximum point.

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