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A New Energy-Efficient Local Metric for Channel-Aware Geographic-Informed Forwarding (CAGIF) in Wireless Sensor Networks

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Abstract

This paper proposes a new energy-efficient local metric, termed as Efficient Advancement Metric (EAM), for Channel Aware Geographic-Informed Forwarding (CAGIF) algorithm, which studies the optimal selection of the relay nodes by taking into account the underlying channel conditions. The proposed metric considers not only the forward distance but also the packet successful probability under a certain channel condition, rather than purely maximizing the forward distance, to choose the most energy-efficient relay node in the geographic-informed routing protocol in a CDMA-based wireless sensor network. The proposed algorithm only requires that nodes have the knowledge of their own location information and the location information of the source and destination nodes. The protocol assumes that nodes could vary transmission range to search for the optimal relay nodes according to this metric. An analytical framework is provided and numerical results show that there exists an optimum distance of a relay node under a certain channel condition to maximize the EAM for any fading conditions.

I. INTRODUCTION

Geographic information based routing algorithms have been demonstrated to represent an effective way of finding the appropriate next hop relay nodes by utilizing the location information while avoiding the large number of control packets necessary for route discovery in wireless sensor networks. Existing literatures [1] [4] usually concentrate on choosing the next hop relay nodes according to the maximum advanced distance in order to minimize the number of hops from the source to the destination node. However, an inarguable fact is that there is often serious fading phenomena [9] during the radio propagations. Consequently, the performance gain of traditional approaches can be traded off for a bad channel condition that requires the repeated packet transmissions to ensure the correct packet reception and hence consumes more energy. Disseminating data information in the deep-fading channel state incurs additional energy burden and it is indispensable to reduce the unnecessary retransmission due to the propagation impairments from physical environment. A straightforward way is to choose the next hop relay nodes under good channel conditions to ensure the correct packet transmission and to avoid the relay nodes in the deep-fading channel state since a bigger successful packet transmission probability increases the energy efficiency of the effective data transmission.

Recently, the algorithm in [5] proposes expected transmission count metric to reduce the total

expected number of retransmissions. Energy efficient forwarding strategies [6] identifies the weak-link problem and makes localized geographic forwarding decision by employing packet reception ratio multiplied with the distance as the metric. ExOR [7] chooses the forwarder with the lowest remaining cost to the ultimate destination and investigates its throughput performance. The algorithm in [8] proposes the normalized advance for geographic routing as the metric to select neighbors with the optimal trade-off between proximity and link cost. Energy efficient forwarding in [9] examines the number of hops that is necessary to reach a destination at distance D as a function of the density of available relay nodes in the presence of fading. The channel-adaptive routing [10] investigates the information efficiency of the channel adaptive routing in a code division multiple access (CDMA) based multi-hop network. However, none of them has studied whether there exists an optimum value of the relay distance corresponding to a certain channel condition by the theoretical model.

In this paper, we first propose Channel Aware Geographic-Informed Forwarding (CAGIF) algorithm that chooses the relay nodes from the links with favorable energy efficiency. Then, we present a new energy-efficient local metric, termed as Efficient Advancement Metric (EAM), which considers not only the forward distance but also the power efficiency of effective data transmission. By exploiting the inherent channel conditions, the proposed algorithm assumes the nodes could adaptively adjust the transmission range and hence chooses a node with the maximum EAM as the next hop relay node by taking into account the channel conditions. The proposed algorithm only requires that nodes have the knowledge of their own location information and the location information of the source and destination nodes. Relay nodes may be chosen randomly via opportunistic contention among the receivers upon hearing the transmission request, where the competition is based on the priority weight that is determined by the EAM. We present an analytical framework to study the optimal selection of a relay node by constructing a finite state Markov chain to model the wireless channel. We argue that there exists an optimum distance of a relay node under a certain channel condition to maximize the EAM for any fading conditions.

The remainder of this paper is organized as follows. Section II describes the system model. Section IV-A presents CAGIF algorithm and the new performance metric. Section IV provides the analytical framework. Section V explains the numerical results and shows the performance in terms of the EAM. Section VI concludes the paper.

II. SYSTEM MODEL

Let us consider a wireless CDMA multi-hop network operating under heavy traffic conditions, where nodes are randomly distributed in the plane according to a two-dimensional Poisson point process with average density λ . Then, the probability of finding k nodes within the region with radius a is

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

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 (DS/BPSK) with rectangular chip pulse, and that nodes transmit at the same transmission power. Following [2] [3], signal to interference and noise ratio (SINR) M is represented as,

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

where P_r is the received signal power, Y is the total interference power, G is the processing gain and μ_0 is the SINR at the receiver in the absence of multiple access interference (MAI). The total MAI signal is assumed to be approximated by a Gaussian random variable.

Depending on the fading status of the channel and the distance between the transmitter-receiver pair, there is different receiving signal strength and thus different SINR. Let μ_t denote the threshold value of SINR for successful packet reception. Note that the probability of packet success is dependant on the coding scheme. According to [3], for a best long code, the packet success probability approaches a step function at a certain value of μ_t . Then, we have the unconditional packet success probability

$$\begin{aligned} P_s &= \int_0^\infty p_M(\mu) f_M(\mu) d\mu \\ &= \int_0^\infty p'_M(\mu) (1 - F_M(\mu)) d\mu \\ &= 1 - F_M(\mu_t) \end{aligned} \quad (2)$$

where $f_M(\cdot)$ and $F_M(\cdot)$ are respectively the pdf and *cumulative distribution function* (cdf) of the random variable M , and the packet success probability $p_M(\cdot)$ is a step function

$$p_M(\mu) = \begin{cases} 1, & \mu \geq \mu_t \\ 0, & \mu < \mu_t \end{cases} \quad (3)$$

A complex channel model is used that considers both large-scale path loss with path loss exponent n and multi-path fading. We use a generic Nakagami- m fading distribution to characterize the multi-path fading, since it is a two-parameter distribution with the Nakagami fading parameter m and the average received power parameter Ω and it can give the best fit to the statistics of signals transmitted over multi-path channels in a land-mobile and indoor-mobile environments via the m parameters. We consider the slowly-varying flat fading and hence the channel remains roughly constant over a time slot. Let P_t and P_r denote respectively the transmission power and the receiving signal strength. Then, we have

$$P_r = \frac{A^2 P_t}{d^n} \quad (4)$$

where A is the channel fading amplitude and d is the distance between the transmitter and receiver and n is the path loss exponent. The channel fading amplitude A is a Nakagami fading random variable, whose pdf [18] is given by

$$p_A(\alpha) = 2\left(\frac{m}{\Omega}\right)^m \frac{\alpha^{2m-1}}{\Gamma(m)} e^{-m\alpha^2/\Omega}, \alpha \geq 0 \quad (5)$$

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

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt, z \geq 0$$

The parameter m characterizes the severity of the fading. 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 $m > 1$ [19].

III. CAGIF ALGORITHM

We first suggest our geographic-informed forwarding algorithm as follows. The basic idea remains the same as the contention-based geographic forwarding algorithms [11] [12], where it is assumed that there is a predefined forwarding area and nodes that reside in this area contend to become the next hop relay nodes. Although various forwarding areas of contention-based geographic forwarding algorithms have been examined in [12], we here adopt $\emptyset$ -degree radian area forwarding and use polar coordinate (R_i, θ_i) in our analysis, where R_i is the distance between the source node and relay node i and θ_i is the angle of the relay node i to the source node and the direct line that combines the source node and destination node. Denote R_f as the distance between the source node and relay node due to fading phenomena. As shown in Fig. 1, the radian sector from $(R_f, -\emptyset/2)$ to $(R_f, \emptyset/2)$ is specified as the geographic region, which the relay nodes should stay in.

Among the nodes that receive a packet and within the forwarding area, the node that achieves the maximum advancement towards the destination node should be the one that forwards the packet. However, the transmission in a deep fading channel state may incur unnecessary energy lost and additional retransmissions are required. Thus CAGIF must have a metric that reflects the likely successful advancing of a packet from any node to the destination and considers not only the forward distance but also the power efficiency of effective data transmission, where the varying channel conditions will be taken into account in physical layer and adaptive transmission range will also be considered in MAC layer.

Let R denote the distance between the transmitter and receiver and P_s denote the probability of successful packet transmission. We define EAM as $R \cdot \cos\theta \cdot P_s$, which is the product of the projection of the distance between the transmitter and receiver to the line that combines the

source node and the destination node and the probability of successful packet transmission. The EAM is an evolution of the expected progress per hop [1] [3] and here, we do not consider the tendency of two nodes to pair up.

In CAGIF, a relay node should be chosen to satisfy

$$\mathcal{R} = \arg_{\forall(R, \theta, A)} \max[R \cdot \cos\theta \cdot P_s]$$

That is, CAGIF algorithm chooses the next hop relay node within the forwarding area that may not only maximize the forward progress but also be in a good channel condition simultaneously.

Based on the instantaneous channel conditions, an increasing transmission range is allowed to achieve a bigger advancement towards the destination and thereby reduce the total number of hops to the destination. However, with an increasing transmission range, there is bigger MAI, which reduces the probability of successful packet transmission and hence reduces the energy efficiency. We, hence, aim to study this tradeoff and find the optimum forwarding distance of a relay node by adjusting the transmission ranges, which can achieve the maximum advancement while maintaining the acceptable MAI in a geographic information based routing protocol.

IV. ANALYTICAL FRAMEWORK

A. MAI Power Distribution in a Generic Nakagami- m Fading Channel

In [20] [21], we generalize the fading channel model and derive the distribution of MAI power under a generic Nakagami- m fading channel model. Hence, we have the cdf of Y expressed as

$$F_Y(y) = \begin{cases} \text{Erfc}\left(\frac{\lambda_t \pi^2 \sigma}{2\sqrt{2y}}\right), & m = 1 \\ \text{Erfc}\left(\frac{3\lambda_t \pi^2 \sigma}{8\sqrt{y}}\right), & m = 2 \\ \text{Erfc}\left(\frac{5\sqrt{3}\lambda_t \pi^2 \sigma}{16\sqrt{2y}}\right), & m = 3 \\ \text{Erfc}\left(\frac{35\lambda_t \pi^2 \sigma}{64\sqrt{2y}}\right), & m = 4 \end{cases} \quad (6)$$

for $y > 0$, where $\lambda_t = \lambda_p$ and σ is a fading parameter. (Note that $\text{Erfc}(x)$ is the complementary error function of the variable x .)

B. Markov Model for Nakagami- m Fading Channels

In CAGIF, we model the wireless channel by constructing a finite state Markov chain. We partition the channel states according to the Q -state Markov model, where Q is the partitioned number of channel conditions of a Nakagami- m fading channel. Fig. 2 shows a sample Nakagami- m fading channel, where the channel fading amplitude α is related to the corresponding channel state q in a Q -state Markov model. Denote α_q^l and α_q^u respectively as the lower and upper threshold values of α for the q ($q = 1, \dots, Q$) channel state interval, where q denotes the different channel states and incremental q means better channel conditions. For each

good channel state, there is a corresponding transmission radius to maximize the EAM. Next, we provide the analysis of the EAM.

C. Analysis of EAM

Substituting Eq. 1 in Eq. 6 in terms of Y , we can obtain the conditional cdf of μ on α as

$$F_{M|A}(\mu|\alpha) = \begin{cases} 1 - F_Y[\frac{3G}{2R^4}(\frac{\alpha^2}{\mu} - \frac{1}{\mu_0})], & \mu < \alpha^2\mu_0 \\ 1, & \mu \geq \alpha^2\mu_0 \end{cases} \quad (7)$$

where α follows a Nakagami-m probability distribution.

Define the multiple-access capability

$$K(\mu, \alpha) = \frac{3G}{2}(\frac{\alpha^2}{\mu} - \frac{1}{\mu_0}) \quad (8)$$

Thus, we can obtain

$$\begin{aligned} & F_M(\mu) \\ &= \int_0^\infty F_{M|A}(\mu|\alpha) f_A(\alpha) d\alpha \\ &= \int_0^{\sqrt{\mu/\mu_0}} f_A(\alpha) d\alpha + \int_{\sqrt{\mu/\mu_0}}^\infty (1 - F_Y[\frac{1}{R^4}K(\mu, \alpha)]) \\ &\quad \cdot f_A(\alpha) d\alpha \\ &= 1 - \sum_{q=1}^Q \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R^4}K(\mu, \alpha)] f_A(\alpha) d\alpha \end{aligned} \quad (9)$$

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

As a result, the EAM can be expressed as

$$\begin{aligned} & R \cdot \cos\theta \cdot P_s \\ &= R \cdot \cos\theta \cdot (1 - F_M(\mu_t)) \\ &= R \cdot \cos\theta \cdot \sum_{q=1}^Q \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R^4}K(\mu_t, \alpha)] \\ &\quad \cdot f_A(\alpha) d\alpha \end{aligned} \quad (10)$$

Therefore, the adaptation mechanism can be defined as

$$\begin{aligned}
& \arg_{\forall(R_q, A_q)} \max \{ R \cdot \cos \theta \cdot P_s \} \\
&= \sum_{q=1}^Q \arg_{\forall(R_q, A_q)} \max \{ R \cdot \cos \theta \cdot \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R^4} K(\mu_t, \alpha)] \\
&\quad f_A(\alpha) d\alpha \}
\end{aligned} \tag{11}$$

where R_q and A_q are respectively the variables R and A in the q -th channel state. Let us define

$$(R \cdot \cos \theta \cdot P_s)_q = R \cdot \cos \theta \cdot \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R^4} K(\mu_t, \alpha)] f_A(\alpha) d\alpha \tag{12}$$

Eq. 12 is a concave function in the variable R and hence there exists an optimum value of R_q to maximize $(R \cdot \cos \theta \cdot P_s)_q$. Therefore, we can find the optimum value of R for each channel state to maximize $R \cdot \cos \theta \cdot P_s$ in Eq. 11 such that transmitter can choose an optimal relay node to achieve the maximum EAM. Next, we examine the thresholds of the partitioned channel states.

D. Determination of Thresholds

We know that the steady state probability of channel conditions can be derived as

$$\begin{aligned}
& Pr[\alpha_q^l < \alpha \leq \alpha_q^u] \\
&= \int_{\alpha_q^l}^{\alpha_q^u} p_\alpha(\alpha) d\alpha \\
&= (\Gamma(m, \frac{m\alpha_q^{l2}}{\Omega}) - \Gamma(m, \frac{m\alpha_q^{u2}}{\Omega})) / \Gamma(m)
\end{aligned} \tag{13}$$

There are many partitioning schemes for determining the thresholds of state intervals in the finite-state Markov channel [14] [15]. In the following numerical results, we simply apply equally probable partition [13] of channel states. Taking the case $m = 1$ as the reference, we determine the thresholds according to

$$Pr[\alpha_q^l < \alpha \leq \alpha_q^u] = \frac{1}{Q+1} \tag{14}$$

where $\alpha_0^l = 0$ and $\alpha_Q^u = 3$ since they cover 99.99% of the pdf values.

V. NUMERICAL RESULTS

With reference to a direct-sequence mobile packet radio network [16] [17], we choose the same system parameters $\mu_t = 6.6dB$ (required BER = 10^{-5} and CRC code gain = $1dB$), $\mu_0 = 26.6dB$ and $\lambda = 10^{-3}$. The parameter σ 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 $\alpha_1^l = 0$ with $\alpha_1^l = \sqrt{\mu_t/\mu_0} = 0.1$ as noted in Eq. 9. Thereafter, we specify $\theta = 0$ to focus on the study of the optimum distance of a relay node corresponding to a certain channel condition.

Fig. 3 shows that EAM versus the distance of a relay node with the varying spreading factor G for different channel conditions of a Rayleigh fading channel when $Q = 2$ and $p = 0.3$. There exists an optimum value of R to maximize the EAM for each partitioned channel state q , which can be obtained by differentiating $R \cdot \text{Cos}\theta \cdot P_s$ with respect to R . We observe that $q = 2$ gains a substantial performance improvement, in terms of EAM, over $q = 1$, since an incremental value of q implies a better channel condition and hence achieve a bigger packet successful probability. With the increasing values of G , there is better EAM. Meanwhile, the optimal distance of a relay node increases with an incremental value of G . This is attributed to the increasing multiple access capability with a bigger spreading factor. Next, we specify G as 64 to investigate the performance of the optimal distance of a relay node to maximize the EAM.

Fig. 4(a), (b) and (c) show that EAM versus the distance of a relay node under the varying number of state partitions of a Rayleigh fading channel respectively in the cases of $Q = 2$, $Q = 3$ and $Q = 4$ when $G = 64$ and $p = 0.3$. Obviously, when we consider the packet successful transmission probability under the varying channel conditions, there is corresponding optimal distance of a relay node to maximize the EAM, under the different number of state partitions of a Rayleigh fading channel. With more number of partitions of channel states, the optimal distance in the best channel conditions increases due to better instantaneous channel states. However, the increasing slope becomes less, which is attributed to that more number of partition approximates the perfect estimation of the instantaneous channel states. Instead, there is even smaller optimum distance and worse EAM in the worst channel condition of $q = 1$. For instance, the illustrated values of $d = 48$, $d = 52$ and $d = 54$ show the maximum value of EAM, for $q = 2$, $q = 3$ and $q = 4$ respectively in the cases of $Q = 2$, $Q = 3$ and $Q = 4$. While, $d = 31$, $d = 27$ and $d = 25$ show the maximum value of EAM for $q = 1$, in the cases of $Q = 2$, $Q = 3$ and $Q = 4$ respectively.

In Fig. 5, we vary the distance of a relay node to observe the EAM under the varying channel conditions respectively in the cases of $m = 1$, $m = 2$ and $m = 4$ of a Nakagami- m fading channel when $G = 64$, $Q = 3$ and $p = 0.3$. We observe that, for any case of m , there is different optimum value of R to maximize the EAM under different values of q . For any case of m , the optimum distance increases with an increasing value of q . For $q = 2$, EAM increases with an incremental value of m , due to less severe fading. However, for $q = 3$, EAM of $m = 4$ is even less than that of $m = 1$ and $m = 2$. This is attributed to the fact that the pdf of Nakagami- m fading attenuation varies with the parameter m . With the increasing values of m and our assumption of the equally probable partition with the reference of $m = 1$, there is bigger cumulative distribution when $q = 2$ than that when $q = 3$ for Nakagami- m fading with $m > 1$.

Fig. 6 shows the optimum distance of a relay node versus the average transmission probability in different channel states of a Rayleigh fading channel for the varying average node density when $G = 64$ and $Q = 3$. As p increases, the optimum distance of a relay node decreases. Although the optimum distance increases with the increasing q due to the better channel conditions, it decreases with an incremental node density, which even may tradeoff the benefit of a good channel condition. For instance, as shown in Fig. 6, the curve of the optimum distance of a relay node when $q = 3$ and $\lambda = 2 \times 10^{-3}$ is lower than that when $q = 2$ and $\lambda = 10^{-3}$. This is due to the fact that an increasing node density indicates more MAI under a certain transmission probability and hence reduces the successful packet transmission probability.

VI. CONCLUDING REMARKS

In this paper, a new local energy-efficient metric of EAM is proposed for CAGIF in a CDMA-based wireless sensor network. 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 good cross-layer combination by effectively integrating routing and MAC as well as physical layer in a geographic-informed CDMA based wireless sensor networks. An analytical framework is provided and numerical results show that there exists an optimum distance of a relay node under a certain channel condition to maximize the EAM for any fading conditions.

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Q	α_1^l	$\alpha_1^u(\alpha_2^l)$	$\alpha_2^u(\alpha_3^l)$	$\alpha_3^u(\alpha_4^l)$	α_4^u
2	0.1	0.8325	3	-	-
3	0.1	0.6367	1.048	3	-
4	0.1	0.5364	0.8326	1.1777	3

Table I

Figure 1

Figure 2

Figure 3

(a) $Q = 2$

(b) $Q = 3$

(c) $Q = 4$

Figure 4

(a) $m = 1$

(b) $m = 2$

(c) $m = 4$

Figure 5

Figure 6