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# Energy Efficiency: Optimal Transmission Rangewith Topology Management in 2-D Ad-hocWireless Networks

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**Abstract.** The Most nodes of ad-hoc wireless networks are batterypowered,therefore limit of energy is one of the critical constraintsof ad-hoc wireless networks' development. This paper analyzesa real two dimensional ad-hoc network that achieves energyefficiency by optimizing the node radio range based on theGeographical Adaptive Fidelity (GAF) topology managementprotocol [1]. This paper derives the optimal transmission rangeof nodes and analyzes both static and dynamic traffic scenariosin both equal-cell and adjustable-cell 2-D GAF models, where theresults show that the adjustable-cell model saves 62.6% energyin comparison to the minimum energy consumption of equal-cellmodel.

**Keywords:**Wireless networks, Energy efficient, 2-D networks.

## 1. Introduction

Energy efficient ad-hoc wireless networks have been widelydeployed, andenergy consumptionof nodes in ad-hoc networksshould be managed efficiently to prolong the network lifetime.The energy consumption of each node varies according toits communication state: transmitting, receiving, listening orsleeping. In [2], the ratios between thelistening, receiving and transmitting states are described as:1: 1.05:1.4. In [3], the authors described the same ratiosas: 1:1.2:1.7. It is necessary to keep as many as possible nodesin sleeping state to maximize the network lifetime.

Geographical Adaptive Fidelity (GAF) [1], one of the topologymanagement protocols, is applied to manage the states ofnetwork nodes and select the multi-hop relay nodes to improveenergy efficiency. Based on the nodes' positions information,the GAF protocol divides the entire network into small virtualgrids, where any node in each grid can communicate with anynode in its adjacent grids. In [4], the authors proposed a linear network GAF model and analyzedboth equal and adjustable grid models. It has been found outthat the adjustable-grid model is more energy efficient thanthe equal-grid model.The work in [5] uses clustering mechanisms to discussenergy saving in rectangular wireless networks. A relationshipbetween optimal transmission range and traffic was derivedbased on static traffic scenario. In this paper, however, weevaluate a two dimensional hexagonal GAF model and GAFprotocol to optimize the total energy consumption of ad-hocnetworks confined in a square space covered by equal oradjustable cells.

## 2. Preliminaries

The energy consumed by ad-hoc wireless network nodes isthe sum of energy consumed for transmitting, receiving andlistening. Based on [6] the energy consumed per second by anode in these three states could be respectively calculated asfollows:

$$E_t = (e_e + e_a R_n) D_t, E_r = (e_e + e_p) D_r, E_l = e_l T_l = e_l (1 - T_t - T_r), \quad (1)$$

where $e_e$ is the energy/bit consumed by the transceiverselectronics, $e_a$ is the energy/bit consumed in the transmitterRF amplifier, $e_p$ is the energy/bit consumed for processing inreceivers, and $e_l$ is the energy/second consumed for listeningto the radio environment: $e_e, e_a$ $and$ $e_p$ are determined by thedesign characteristics of the transceivers. Based on [7] and [5],the typical values of these parameters: $e_e = 3.32 \times 10^{-7} J/bit$,$e_p = 6.8 \times 10^{-8} J/bit$, $e_e = 8 \times 10^{-11} J/bit/m^2$, for n = 2,where n is the power index of the channel path loss, which isbetween 2 and 4. R is the node transmission range; $D_t$ and $D_r$are the transmitted and received traffic data bits, respectively. $T_t$ and $T_r$ denote respectively the time for transmitting andreceiving the traffic data of a grid, which can be expressed asfollows:

$$T_t = \frac{D_t}{d_R}, T_r = \frac{D_r}{d_R} \qquad (2)$$

where$d_R$ is the transmission or received data rate(bits/second) of each network node. $T_l$, which denotes thetime spent listening to the radio environment in one second,is: $T_l = 1 - T_t - T_r$. $e_l$is related to $d_R$as: $e_l = e_e \times d_R$.

## 3. Static traffic in equal-cell model

Here we consider a scenario where an ad-hoc network ismanaged by an equal-cell GAF model, where static traffic(i.e., traffic rate is constant) is flowing along the network. Thistypically occurs between a source node and a sink node, wheretraffic is only generated by the source node and forwarded bythe intermediate nodes.

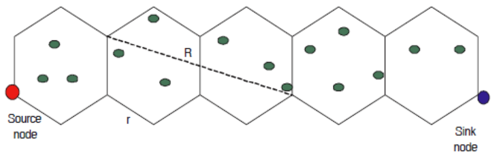


Fig. 1: Equal-cell GAF model.

Fig. 1 depicts the equal-cell GAF model, where we assumetraffic data (*D*) is transmitted between any two nodes in an adhocnetwork managed by this GAF model. Let L denotes thedistance separating these two nodes, then based on the equalGAF model, the number of cells, *m*, betweenthese two nodes,is:

$$\mathrm{m} = \frac{L}{\sqrt{3}r} \qquad (3)$$

where*r* represents the side length of hexagon cells. Since anynode in one cell is able to communicate with any nodes inits neighboring cells, the node transmission range (*R*) in eachis:

$$\mathrm{R} = \sqrt{13}r \qquad (4)$$

The total energy consumed in the$\mathrm{i}^{th}$ grid,$E_i$, is the sum of theenergy consumed in the listening, transmitting and receivingstates of the nodes in this grid, thus:

$$E_i = E_t + E_r + E_l = e_p D + e_l + e_a R_i^n D \qquad (5)$$

where$R_i$is the transmission range of nodes in the$\mathrm{i}^{th}$cell, and it isconstant in this scenario. Therefore,based on equations 3, 4 and 5, the energy consumedfor end-to-end data transmission can be expressed asfollows:

$$E_{total} = \sum_{i=1}^{m} E_i = m \times E_i = \frac{L}{\sqrt{3}r}\left[e_p D + e_l + e_a\left(\sqrt{13}r\right)^n D\right] \qquad (6)$$

To determine the minimum energy consumption of thenetwork nodes, we take the first derivative of $E_{total}$ in termsof side length of hexagon cell, *r*, and let $\frac{\partial E_{total}}{\partial r} = 0$, where we assume *n* = 2:

$$E'_{total} = \left(-e_p D - e_l - W^2 e_a D\right) L r^{-2} + 4LDe_a = 0. \qquad (7)$$

By solving equation 7 for *r*, we getthe optimal grid length$r^*$:

$$r^* = \sqrt{\frac{e_p D + e_l}{13 e_a D}}, \qquad (8)$$

Based on equation 4, theoptimal transmission range, $R^*$, can be described as follows:

$$R^* = \sqrt{\frac{e_p D + e_l}{e_a D}}, \qquad (9)$$

Equation 9 shows that $R^*$ only relates to the static network traffic data ($D$) andelectronic parameters ($e_p, e_a, e_l$), and the distance betweensource and sink nodes does not affect the result.

# 4. Dynamic traffic in equal-cell model

In contrast to the previous scenario, we consider a dynamictraffic where traffic data rate changes along the network.Without loss of generality, we assume that the traffic datais uniformly generated along the network. Let γ(bits/m2)denotes the traffic intensity.

## 4.1. 2-D GAF protocol

Fig. 2 depicts a two dimensional network (2-D) managedby the equal-cell GAF model. The sink node lies inthe centre of the central hexagon cell, where traffic data in the network is forwarded tothe sink node according to our proposed 2D GAF protocol.In this work, the cells are classified into Communication BackboneCells (CBCs) and Normal Cells (NCs). Six CBCs are extendedfrom the six directions of the central hexagon sides, whichrepresent the dark cells in Fig.2, where the other cells areconsidered NCs. Since CBCs are symmetrical, we focus onone of them. Thus, we divide the entire network into six areas,as shown in Fig.2.

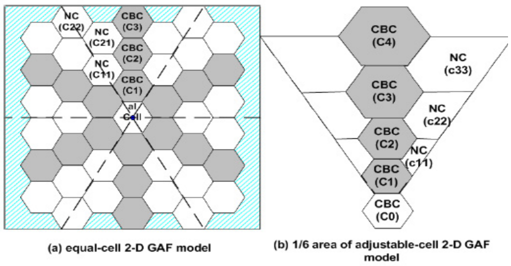


Fig. 2: 2-D equal and adjustable cell GAF model.

First, nodes in the central cell do not receive traffic fromother cells; they only transmit their own traffic to the sinknode. Second, nodes in NCs transmit and forward traffic toother NCs or CBCs nearer the central cell. It is noteworthythat, in this step, NCs which are equidistant to two directionalCBCs, their traffic is clockwise forwarded to avoid its splittingthe NCs. Fourth, arrived and generated traffic in CBCs isforwarded to the CBCs nearer the central cell until it reachesthe sink node. The number of NCs of one directional CBCs isequal to the number of NCs in 1/6 area of the entire network.

## 4.2. Network traffic calculation

As shown in Fig.2, the CBCs arelabeled according to their distance to the sink node of centralcell. Let $C_0$ denotes the central cell and $C_1$ denotes the CBCsconnected to the central cell, where each is connected to oneNC denoted as $C_{11}$. Based on this, the CBCs next to $C_1$ aredenoted by $C_2$, and each $C_2$ is connected to at least two NCsdenoted by $C_{21}$ and $C_{22}$. Thus, the CBCs next to $C_{m-1}$sare denoted by $C_m$, and each$C_m$ is connected to at least*2m-1* NCs denoted by $\{C_{m1}, C_{m2}, \ldots C_{mm}\}$. Based onthis labeling and our proposed 2D GAF protocol, the networktraffic of each cell (in 1/6 entire network area) can be derivedas follows:

$$C_0: D_{r0} = 0, D_{t0} = \frac{1}{6}\ S\gamma;\ C_1: D_{r1} = \left[\frac{1}{6}(W^2 - S) - S\right]\gamma, D_{t1} = \frac{1}{6}(W^2 - S)\gamma; C_{11}: D_{r11} = 0, D_{t11} = S\gamma; C_m: D_{rm} = \left[\frac{1}{6}(W^2 - S) - (2m-1)S\right]\gamma, D_{tm} = \left[\frac{1}{6}(W^2 - S) - (2m-2)S\right]\gamma; C_{m1}: D_{rm1} = (2m-3)S\gamma, D_{tm1} = (2m-1)S\gamma; C_{m2}: D_{rm2} = (2m-5)S\gamma, D_{tm2} = (2m-3)S\gamma; \ldots\ldots C_{mm}: D_{rmm} = 0, D_{tmm} = S\gamma; \qquad (10)$$

where$W$ is the side length of our square network model and$S$ represents the area of the hexagonal cell.

## 4.3. Energy consumption

In an equal-cell GAF model, the transmission range ofnodes is determined by the GAF protocol. Consider thetransmission range in $C_0$ ($R_0$) is r, then the transmission rangeof nodes in remaining cells is$\sqrt{13}$r. Within one second time,based on equations 1, 2 and 10, we can calculate the energyconsumed in each cell as: $C_0: E_0 = E_{t0} + E_{r0} + E_{l0} = e_l + \frac{1}{6} e_a r^n S\gamma$; $C_1: E_1 = e_p \left[\frac{1}{6}(W^2 - S) - S\right]\gamma + e_l + e_a \frac{1}{6}(W^2 - S)\left(\sqrt{13}r\right)^n \gamma$; $C_{11}: E_{11} = e_l + e_a \frac{1}{6}\left(\sqrt{13}r\right)^n S\gamma$; $C_m: E_m = e_p \left[\frac{1}{6}(W^2 - S) - (2m-1)S\right]\gamma + e_l + e_a\left(\sqrt{13}r\right)^n \left[\frac{1}{6}(W^2 - S) - (2m-2)S\right]\gamma$; $C_{m1}: E_{m1} = e_p(2m-3)S\gamma + e_l + e_a\left(\sqrt{13}r\right)^n (2m-1)S\gamma$; ... ... $C_{mx}: E_{mx} = e_p\left(2m-(2x-1)\right)S\gamma + e_l + e_a\left(\sqrt{13}r\right)^n \left(2m-(2x-1)\right)S\gamma$; ... ... $C_{mm}: E_{mm} = e_l + e_a \frac{1}{6}\left(\sqrt{13}r\right)^n$;

(11)

The total energy consumed in the 1/6 network can be classifiedinto two types: $E_{NC}$ (energy consumed in Normal Cells)and $E_{CBC}$ (energy consumed in Communication BackboneCells). Based on equation 11,given S $\frac{3\sqrt{3}}{2} r^2$ *and* $n = 2$,the energy consumed in the 1/6 area network is:

$$E_{total} = E_{NC} + E_{CBC} = e_l + \frac{1}{6} e_a r^2 S\gamma + m\left[\frac{3}{2} e_l + 13 e_a r^2 \left(\frac{1}{6} W^2 \gamma\right) + \frac{1}{6} e_P W^2 \gamma + \frac{1}{6} S\gamma\right] + \frac{1}{2} m^2 [e_l - 13 e_a r^2 S\gamma - 3 e_P S\gamma] + \frac{1}{3} m^3 [13 e_a r^2 S\gamma + 5 e_P S\gamma], \quad (13)$$

where*n=2*.Since the entire square network should be covered by thehexagonal cells, one condition should be achieved, which is

$$(2m+1) \times \sqrt{3}r = W \quad (14)$$

Thus, *r* can be represented as:

$$r = \frac{W}{\sqrt{3}(2m+1)} \quad (15)$$

By replacing r from equation 15 in equation 13, we obtainthe energy consumed in 1/6 area network as a function of thenumber of CBCs ($m$).

## 5. Dynamic traffic in adjustable-cell model

In dynamic traffic scenario,intermediatenodes near a sink node which process more traffic, should have a smaller radio range to minimizetheir energy consumption. From equations 8 and 9, nodes nearthe sink can adjust their transmission range to the optimalvalue, which represents the optimal trade-off between energyconsumption and amount of traffic processed by these nodes.

As shown in the 1/6 area of the network in Fig. 2, thenfollowing the adjustable-cell hexagonal GAF model this areais divided into adjustable hexagonal CBC cells and anomalousNC cells. And the 2D GAF protocol functions in the samemanner as in the equal-cell GAF model. Each CBC has onlytwo symmetrical NCs, which are parts of hexagonal cells,where their traffic is transmitted directly to the CBC closerto the central cell. The transmission range of nodes in CBCcell can be calculated from 8, where *D* is replaced by $D_t$representing the dynamic traffic. The traffic of each cell can be derived as follows:

$$C_0: D_{r0} = 0, D_{t0} = \frac{1}{6} S_0\,\gamma;\ C_1: D_{r1} = \left[\frac{1}{6}(W^2 - S_0) - S_1\right]\gamma, D_{t1} = \frac{1}{6}(W^2 - S_0)\gamma; C_{11}: D_{r11} = 0, D_{t11} = S_{11}\gamma; C_m: D_{rm} = \left[\frac{1}{6}(W^2 - S_0) - S_0 - S_1 - S_{11} \ldots - S_m\right]\gamma, D_{tm} = \left[\frac{1}{6}(W^2 - S) - S\right]\gamma; \ldots\ldots C_{mm}: D_{rmm} = 0, D_{tmm} = S_{mm}\gamma; \quad (16)$$

where$D_{rm}$> 0 when the 1/6 area network is completelycovered. We assume that hexagonal cells $C_0$ and $C_1$ aresimilar, where the area of each cell can be calculated, then based on equations 8and 16, the traffic of each cell can be calculated.As any node in one cell can forward data to any node ofits adjacent cells, we can derive the node transmission rangeof each cell, and the energy consumed in each cell can be calculated, where the total energy of 1/6 area networkcan be calculated as:$E_{total} = \sum_{i=1}^{m}(E_i + E_{ii})$.

## 6. Numerical results

To evaluate the performance of our proposed 2-D GAFmodel and protocol, we have conducted two experiments tostudy the relationship between the node optimal transmissionrange and network traffic, and to compare the energyconsumption of equal and adjustable-cell GAF models. Inboth experiments, nodes are uniformly distributed in the cellscovering network and traffic is generated following Poissondistribution.

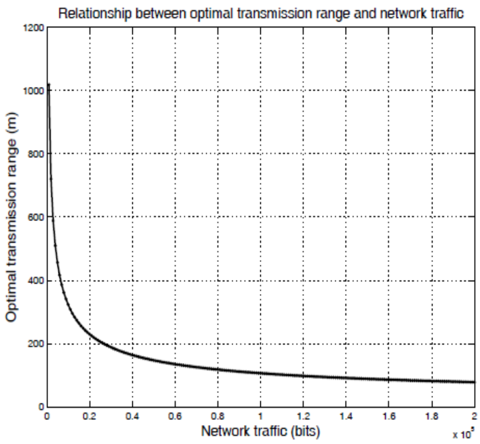


Fig. 3: Optimal transmission radio range VS. network traffic.

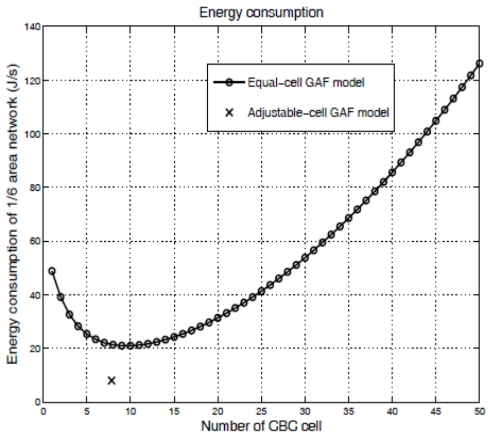


Fig. 4: Comparison of energy consumption.

As a result, Fig. 3 depicts the relationship between the optimaltransmission range and network traffic. Fig. 3 illustratesthat the optimal radio transmission range decreases sharplywhen the traffic data flowing in the network is relatively low.Therefore, the global network energy can be minimized byminimizing the number of nodes involved in traffic transmission,which corresponds to a larger node transmission range.The analysis agrees with this observation and predicts thistrend, where a large number of nodes are in the sleeping stateand therefore the transmission range is large. Based on theresult shown in Fig. 3, the majority of network nodes are inthe sleeping state when the transmitted traffic data is less than$0.3\times 10^5$ bits. It is noteworthy that when the network traffic islarge, the optimal transmission range, $R^*$, takes smaller valuesand therefore the optimal grid length becomes smaller.

Fig. 4 gives the energy consumption comparison betweenequal and adjustable cell GAF models, where $E_{total}$ wascalculated in function of the number of CBCs, m. Fig. 4 shows the minimum energyconsumption of 1/6 area network ($E_{totalmin}$ = 20.97J) isachieved when m = 10, where the side length of each cell$r$ is 27.49m. When the number of cells is small, the lengthof each grid is large. Therefore, the $d^n$ propagationloss component dominates the energy consumption, where theenergy consumption decreases for $m< 10$. However, whenthe number of grids is large, the length of each grid is small.Hence, the $d^n$ propagation loss component becomessmaller, where the transmitter and receiver electronics energyconsumption per bit become large. Therefore, the energyconsumption increases linearly with the number of grids for$m> 10$.

In our adjustable-cell GAF models, we have calculated theenergy consumption of 1/6 area network based on equations 8to 18, which is represented by X in Fig. 4. The energyconsumption of adjustable-cell model occurs when $m$ = 8.Apparently the energy consumption of adjustable-cell model issmaller than the minimum value of the energy consumption ofequal-cell model, which means that the adjustable-cell modelis more energy efficient than the equal-cell model. Based onthese results, we have found out that the adjustable-cell modelcan save up to 62.6% energy in comparison to the minimumenergy consumed in the equal-cell Model.

## 7. Conclusion

In this paper, we have derived the relationship betweenthe optimal transmission radio range and network traffic. Wehave also derived the relationship between network energyconsumption and number of grids in the equal-cell GAFmodel, which enabled us to calculate the minimum energyconsumption in this model. Besides, we calculated the energyconsumption in adjustable-cell GAF model based on the networknode optimal transmission radio range. The results showthat about 62.6% energy is saved by using the adjustable-cellGAF model compared to the minimum energy consumptionin equal-cell GAF model.

## 8. References

[1] Y. Xu, J. heidemann, and D. Estrin, "Geography-informed energy conservationfor ad hoc routing," in Proceedings of ACMMobil'01, pp. 70–84,July 2001.

[2] M. Stemm and R. H. Katz, "Measuring and reducing energy consumptionof network interfaces in hand-held devices," IEICE Transactions onCommunications, vol. E80-B(8), no. 8, pp. 1125–1131, 1997.

[3] B. J. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: anenergy-efficient coordination algorithm for topology maintenance in adhoc wireless networks," Wireless Networks, vol. 8, pp. 85–96, September2002.

[4] Q. Gao, K. J. Blow, D. J. Holding, I. W. Marshall, and X. H. peng, "Radiorange adjustment for energy efficient wireless sensor network," Ad hocNetworks, vol. 4, pp. 75–82, January 2006.

[5] B. Yin, S. Hongchi, and Y. Shang, "Analysis of energy consumption inclustered wireless sensor networks," in Wireless Pervasive Computing,2nd International Symposium on, pp. 102–114, Feb 2007.

[6] M. Bhardwaj, T. Garnett, and A. P. Chandrakasan, "Upper bounds onthe lifetime of sensor networks," in Proceedings of ICC'01, pp. 785–790,June 2001.

[7] W. R. Heinzelman and A. C. H. Balakrishnan, "Energy-efficient communicationprotocol for wireless microsensor networks," in Proceedings ofHICSS'00, vol. 2, pp. 4–7, January 2000.