Energy Optimization with Adaptive Transmit Power Control for UAV-Assisted Data Transmission in VANETs

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Abstract. Time for unmanned aerial vehicle (UAV) assisted vehicular ad hoc networks (VANETs) to promote the efficient data transmission is limited. To this end, improving the endurance of UAV has become a crucial issue. In this paper, we first propose an energy optimization model to improve the endurance of UAV, which consider not only the flying energy, but also communication energy. By considering the relative position between UAV and vehicle, adaptive transmission power is applied to communication energy consumption. Second, in order to verify the existence of the solution, we use Rolle's theorem and the monotonicity of the function to prove the objective function, and obtain the approximate solution of the objective function by using the principle of inequality. Finally, compare with optimized algorithm and algorithm without optimized communication energy, and our proposed algorithm which performance is better than the existing energy optimization algorithms.

Keywords: Adaptive transmit power control · Relative position · Energy optimization

1 Introduction

With the process of urbanization, social problems and contradictions related to vehicle have gradually become prominent. However, due to some features such as intermittent network connectivity [13] and small network coverage, there will causing road traffic accidents by lack of information interaction between vehicles.

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To deal with these issues, UAV can be utilized to cooperate with VANETs which flexible, fast moving, and low cost [7]. Additionally, the energy of UAV is limited. Therefore, energy optimization of UAV should be developed to extend the endurance of UAV and reduce the service time [1].

Energy optimization of UAV is different from traditional base stations, which need extra energy to maintain flight. Simultaneously, different trajectories will affect energy consumption. In [8], Optimize the trajectory of the UAV by considering the relationship between the communication throughput and the propulsion energy of the UAV, the energy efficiency of maximizing the data transmission rate and minimizing the energy has been studied. Mozaffari M. and Saad W deploy multiple UAVs as mobile base stations to meet the user's rate requirements, a transmission method is proposed to minimize the transmit power in [5]. To this end, in [9], the derivation of the propulsion power consumption model of the UAV, joint optimization of the trajectory and allocate communication time. Consequently, special single-fly-hover energy optimization is studied. In [3,10,11], energy optimization by optimizing location deployment and performance of UAV. In addition, some studies consider the UAV are employed as mobile relays by optimize the trajectories to get better communication performance [15,16]. These methods are not consider dynamic sensor nodes, it seems more significance to consider the energy optimization under dynamic nodes.

Adaptive transmit power control means that the transmit power has the ability to adapt autonomously, which environmental conditions of communication between sensor nodes has change in a wireless sensor network. In [2], proposed that the relationship between transmitted power and received power in one clear line of sight (LoS) path. In [6], the authors used to control the transmit power by controlling the network topology. In [17], the differences of power consumption and data rate between fixed transmit power and adaptive transmit power are analyzed and shows that FTP has a positive impact on the data rate and power consumption performance. Amir Haider and Seung-Hoon Hwang [12] proposed A-TPC algorithm with SB-SPS, the algorithm is better in packet reception ratio. In the UAV-assisted wireless communication network, Kendeepan et al. in [4] considered that there would be a certain amount of communication energy consumption, proposed a real-time adaptive cooperative transmission scheme for dynamic selection between direct links and cooperative links to improve energy use efficiency.

However, all the above presented works assumes nodes are stationary, consider dynamic nodes, such as vehicles and the model which considering the UAV's adaptive transmit power and relative position at the same time is rarely discussed. More importantly, our model can greatly reduce the energy consumption and enhance service performance. Specifically, the contributions and motivations of this paper are as follows:

- First, We systematically studied the correlation between the relative position and the adaptive transmission power, and propose an energy optimization model that can improve UAV broadcast vehicle information and meet certain communication service requirements.

– Second, the feasibility and effectiveness of the model are verified by the proof of the objective function by Roll's theorem and the inequality theorem.

The remainder of this paper is organized as follows: In Sect. 1, it presents the system model of adaptive transmit power improvement and explains in detail. In Sect. 2, we describes the implementation method of the algorithm. In Sect. 3 demonstrates our proposed energy performance based on adaptive power, and presents analysis followed by simulation results. Finally, Sect. 4 summarizes the final results.

2 System Model

In this paper, we design a scenario in which the front and rear ends of the road deployed road side unit (RSU) that collect information on road traffic conditions, as shown in Fig. 1, by deploying multiple UAVs in three-dimensional space to consist UAV network, besides we consider a segment with unidirectional traffic flow, UAV can provide higher coverage in instance and broadcast traffic information to other vehicles instantly. We assume that all vehicles can be served by stationary and mobile units, and the strong mobility of UAV can provide better information services for the entire road network.

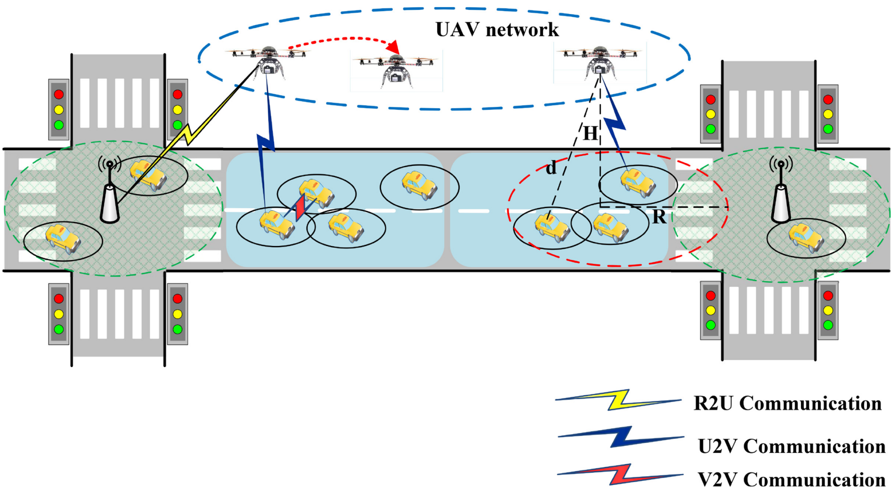

Fig. 1. Overview of UAV assisted vehicular in areas not covered by RSU

In addition, We assume that a section of RSU that is not covered is divided into a series of subsegments, and each road section is provided with a UAV to provide network services. When the UAV is flying in the road section with communicates with cluster head vehicle, speed remains the same. Assume that the minimum service time of UAV is T, the speed of UAV is ν, and the coverage radius is R. Because the height of UAV is stable and large, therefore the width of the road can be ignored, compared with the transmission range between vehicle and UAV. That is we does not consider the left and right movement of UAV and cluster head vehicle.

Due to the limitation of the range of communication for all vehicles, several clusters are automatically formed, and a UAV only communicates with the one cluster head vehicle. We assume the vehicle's position information and speed are already known by the UAV and the vehicle's arrival rate in the road subsection satisfies the Poisson distribution, the vehicle travels at different speeds in different directions and speed of vehicle satisfies $\nu_0 \in [\nu_{min}, \nu_{max}]$, moreover speed of the cluster head vehicle in the subsegment remains the same, and driving forward direction remains the same. Similarity, timing starts when vehicle entering the coverage of UAV, the relative position between the cluster head vehicle and the UAV's vertical projection is x. We assume that there is only one clear Los path between the transmitter and receiver in the free space propagation model, so the distance between the UAV and the cluster vehicle can be expressed as

$$d(x) = \sqrt{x^2 + H^2} \tag{1}$$

For ease of exposition, we ignore the effects of ground reflection models. Note that in practice, the distance between the UAV and the cluster head vehicle affect on the channel quality. Furthermore, the Doppler effect is also well compensated due to the mobility of the UAV. Therefore, according to the free-space path loss model, the channel gain in service time from the UAV to the cluster head vehicle can be expressed as

$$h(x) = \beta d(x)^{-\xi} \tag{2}$$

Where β denotes the channel power gain at a reference distance of 1 meters. ξ is the path loss exponent($\xi \geq 2$). Generally, the received power of a vehicle is related to the distance between the UAV and the vehicle, Therefore, the received signal strength [14] at a cluster head vehicle from the corresponding UAV can be given by

$$P_r(x) = P_t(x)h(x) \tag{3}$$

Where $P_t(x)$ denoted the transmitted power of UAV to the cluster head vehicle. $P_r(x)$ denoted the received power of cluster head vehicle. In this paper, we assume that the vehicle's received power is greater than the threshold α, so UAV can communicate with cluster head vehicle. Therefore, we have

$$P_r(x) \geq \alpha \tag{4}$$

Obviously, given threshold α, we can get the minimum transmitting power of the UAV varies with relative position x as

$$P_t(x) = \frac{\alpha}{h(x)} = \frac{\alpha}{\beta}(H^2 + x^2)^{\xi} \tag{5}$$

Besides, we know the energy consumption of UAV has two main aspects. On the one hand, energy consumed by the UAV to maintain flight and attitude propulsion, on the other hand, communication energy which used to communicate with sensor nodes on the ground, such as vehicle, base station etc.

Generally speaking, the propulsion energy of a UAV is mainly determined by the speed and acceleration of the UAV and the time of acceleration is short, in order to easy to analyze the speed of the UAV, we ignore the energy consumed by the UAV for acceleration and deceleration. Obviously, the left and right trajectory of the UAV is uncertain. Thus, the propulsion energy of the UAV can be expressed as

$$E_f = \frac{MR\nu^2}{\nu - \nu_0} \tag{6}$$

Where M denotes the weight of UAV. It can be seen that the greater the mass of the UAV, the more energy it takes to overcome gravity to do work, and the energy consumption of UAV increases rapidly with speed. In practice, although the communication energy consumed by UAV is very small, it is important for calculating energy. In this paper, we consider the coverage is large, in order to maintain such a large communication range, a large amount of communication energy will be consumed. In addition, the height of UAV is certain, the communication energy of UAV only decided by the distance between the UAV and the cluster head vehicle which actually related to the size of the relative position x between the UAV projection and the cluster head vehicle. We observed that there is no influence of the ground objection, so the vehicle's received power can be expressed as

$$\begin{aligned} E_o &= \int_R^0 P_t(x)\frac{R-x}{\nu-\nu_0}dx + \int_0^R P_t(x)\frac{R+x}{\nu-\nu_0}dx \\ &= \int_0^R P_t(x)\frac{2x}{\nu-\nu_0}dx = \int_0^R \frac{\alpha}{\beta}(H^2+x^2)^{\frac{\xi}{2}}\frac{2x}{\nu-\nu_0}dx \end{aligned} \tag{7}$$

Based on the above, we can get the total energy consumption of the UAV as

$$E = E_f + E_o \tag{8}$$

The UAV needs to chase with the vehicle ahead and provide the real time traffic information, and the communication time between the UAV and the vehicle greater than T, which the interaction of information is considered complete. Besides UAV have a maximum speed limit, and other constraint conditions are satisfied as

$$\nu > \nu_0 \tag{9}$$

$$\frac{2R}{\nu - \nu_0} \geq T \tag{10}$$

$$\nu \leq \nu_{max} \tag{11}$$

It can be seen from the limiting conditions that if the speed of UAV is greater, the communication time will be shorter. We assume that the maximum speed of the UAV is large, and the optimal speed of the UAV is always less than the maximum speed of the UAV, therefore we have

$$\nu \leq \frac{2R}{T} + \nu_0 \tag{12}$$

Because the energy of the UAV is limited, and exceed a certain amount of energy consumption and need to be charged in time. Here we set the total energy of the UAV is ϵ, and the energy constraints are

$$E \leq \epsilon \tag{13}$$

3 Analysis

3.1 Problem Formulation

Based on the above discussions, we formulate the UAV energy minimization problem to service one cluster head vehicle as

$$\min_{\nu} \quad \{\frac{MR\nu^2}{\nu - \nu_0} + \int_0^R \frac{\alpha}{\beta}(H^2 + x^2)^{\frac{\xi}{2}} \frac{2x}{\nu - \nu_0} dx\} \tag{14a}$$

$$s.t. \quad E \leq \epsilon \tag{14b}$$

$$\nu_0 < \nu \leq \frac{2R}{T} + \nu_0 \tag{14c}$$

Note that the constraint (14c) is a non-convex constraint, therefore, the problem is hard to solved. For ease of presentation, we use B denote these values, that is $B = \frac{\alpha}{\beta}\int_0^R (H^2 + x^2)^{\frac{\xi}{2}} 2x dx$, and use $V = \frac{2R}{T} + \nu_0$. Thus, our model can be simplified as

$$\min_{\nu} \quad \{\frac{MR\nu^2}{\nu - \nu_0} + \frac{B}{\nu - \nu_0}\} \tag{15a}$$

$$s.t. \quad E \leq \epsilon \tag{15b}$$

$$\nu_0 < \nu \leq V \tag{15c}$$

3.2 Problem Decomposition

In this section, in order to consider easiest one case, we omit constraint to easy to solve, A generic function is defined as follow:

$$E(\nu) = \frac{MR\nu^2}{\nu - \nu_0} + \frac{B}{\nu - \nu_0} \tag{16}$$

The image of the objective function resembles a check mark function. The difference in the value of T will affect the optimal solution. Therefore, we classify and discuss the objective function.

Theorem 1. *if $\nu > \nu_0$, the optimal solution to energy-minimization problem is*

$$\nu^* = \sqrt{\frac{B + MR\nu_0^2}{MR}} + \nu_0 \tag{17}$$

correspondingly, the minimum energy consumption of the UAV is

$$E(\nu^*) = \frac{B + MR{\nu^*}^2}{\nu^* - \nu_0} \tag{18}$$

Proof. See Appendix A

By considering that the maximum speed V of the UAV is greater than or less than the optimal speed ν^*, that will cause different energy levels. Therefore, we divide the maximum speed V of the UAV into two parts.

In part one, the speed V of the UAV cannot reach the optimal speed $\nu^*$of the UAV, that is $V < \nu^*$. According Theorem 1, the optimal value is unique. And the interval of speed is $\nu_0 < \nu \leq V < \nu^*$, The reciprocal of the $E^{'}(\nu)$ is less than 0, that is $E^{'}(\nu) < 0$, indicating that the $E(\nu)$ monotonically decreasing. So the energy consumption of UAV decreases as ν increases.

In the interval $\nu_0 < \nu \leq V$, the optimal solution to energy-minimization can be express as

$$\nu^* = V \tag{19}$$

correspondingly, the minimum energy consumption of the UAV is

$$E(\nu^*) = \frac{B + MRV^2}{V - \nu_0} \tag{20}$$

In part two, the speed V of the UAV great than the optimal speed ν^* of the UAV, that is $V > \nu^*$. And the optimal value ν^* at this time is $\nu^* \in (\nu_0, V)$. the optimal solution to energy-minimization can be obtain as

$$\nu^* = \sqrt{\frac{B + MR\nu_0^2}{MR}} + \nu_0 \tag{21}$$

Similarly, the optimal energy consumption of UAV is

$$E(\nu^*) = \frac{B + MR{\nu^*}^2}{\nu^* - \nu_0} \tag{22}$$

4 Performance Evaluation and Results

In this section provides numerical results to validate the proposed design. The speed of the cluster head vehicle $\nu_0 = 20\,\text{m/s}$, and the threshold value of the cluster head vehicle's received power is set $P_r = 10\,\text{dBm}$. Set the communication time T and $\xi = 2$. Without loss of generality, we assume that when the UAV communicates with the cluster head vehicle, the speed of the UAV remains unchanged and only serves one cluster head vehicles within range.

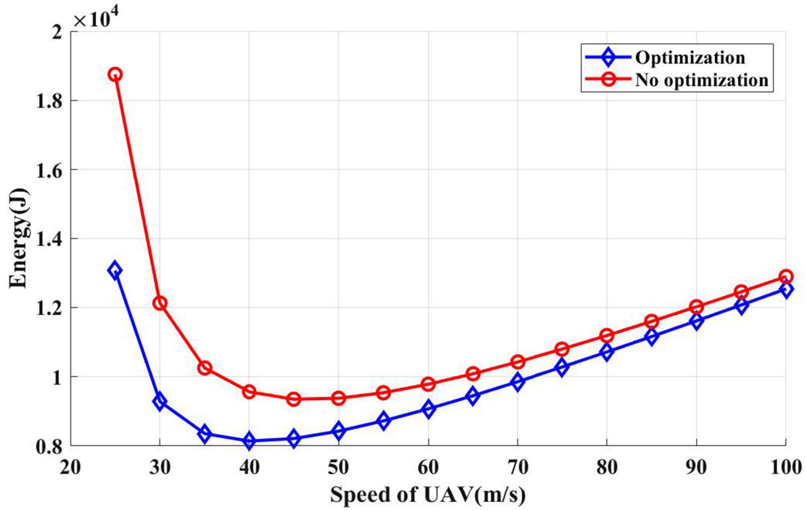

Fig. 2. Energy consumption of UAV at different speeds

To verify the theoretical analysis, we first plotted the trend of UAV energy as a function of UAV speed. As shown in Fig. 2, we can clearly see that as the speed of the UAV increases, the energy consumption continues to increase. In addition, since the speed of the vehicle is set to 20 m/s, it can be found that when the speed of the UAV communicates with the vehicle, the closer it is to the speed of the vehicle, the longer it takes to service the vehicle, and the more energy consumption during data transmission. And in order to verify the advantages of our algorithm in energy optimization, we compare it with algorithms that have not been optimized in communication energy. We observed that the greater the UAV speed, the shorter the data transmission time, and the closer the optimization algorithm is to the energy without the optimization algorithm in energy consumption. On the whole, the optimized algorithm will save a certain amount of energy.

Next, we consider that the size of the UAV's coverage radius is related to the UAV's transmit power which affects the energy consumption. In Fig. 3, we plotted the changes in the energy of the two algorithms with the UAV's coverage radius. It can be seen that as the radius R increases, the energy consumption of the UAV also increases accordingly. Because of the large range of implementation. The coverage of the UAV needs a lot of power, which will consume a lot of communication energy. Because this paper uses adaptive transmit power, as long as it guarantees a certain communication time, it is considered that the energy under the optimization algorithm is completed and the performance is improved compared with the algorithm without optimization.

Similarly, we plotted the energy consumption trends at different altitudes. We found that the energy consumption under the optimized algorithm is more energy-efficient than the optimized algorithm in Fig. 4, the optimized algorithm

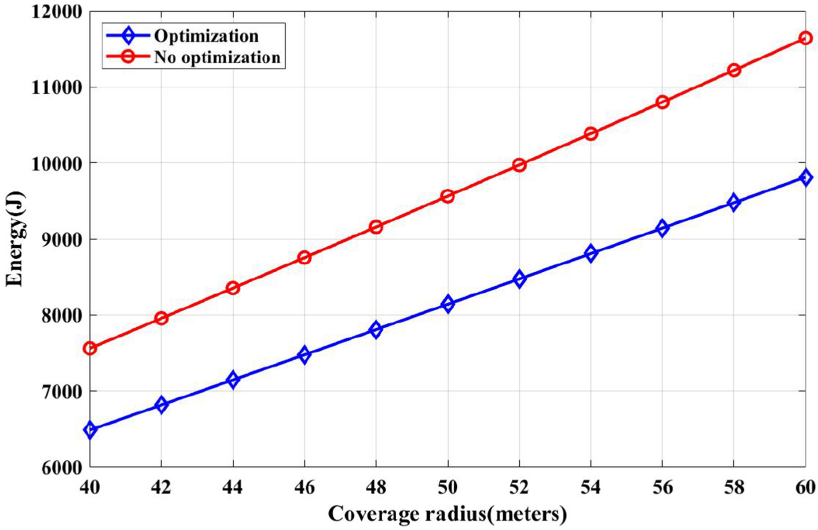

Fig. 3. Energy consumption of UAV at different coverage radius

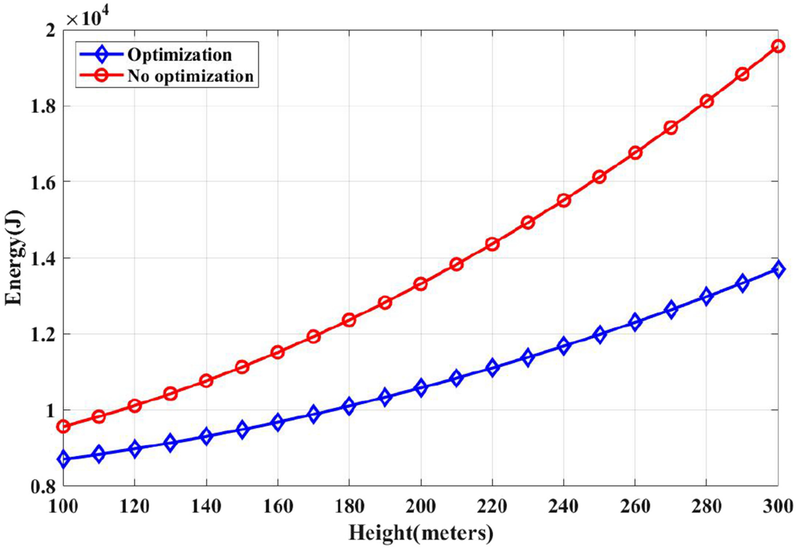

Fig. 4. Energy consumption of UAV at different heights

improves the endurance of the UAV when the distance between the UAV and the cluster head vehicle is increased. And the threshold value of receive power set by the vehicle is not changed, the energy consumption is also increased as the altitude is increased. We further found that this effect is greater with increasing altitude.

We observe that the energy consumption of UAV under the same path loss exponent, and choose the optimal speed according to the speed of different cluster head vehicles, thereby reducing the energy consumption of UAV. Thus we have not included those results of different path loss exponent and analysis because of space limitation in this paper.

5 Conclusion and Future Work

In this paper, we design and evaluate energy optimization algorithms with adaptive transmit power. In the area not covered by RSU, vehicles are divided into multiple clusters through V2V communication. Due to the carry and forward mechanism, there will be a certain delay. UAVs are deployed to assist in wireless communication, which reduces the delay and reduce traffic accident caused by untimely access to information. Our numerical results show that the proposed energy optimization algorithm reduces the energy consumption to compared with the traditional energy algorithm, and can guarantee the minimum communication time requirements.

In the future, we would like to consider the multiple cluster head vehicle into the model, which provide communication between multiple vehicles for real-time information interaction. In addition, we also would like to set different directions of vehicle to deploy UAV rationally.

Appendix A

When $\nu > \nu_0$, the problem $E(\nu)$ is differentiable on the interval (ν_0, ∞), there is only one stable point $\nu^\sharp$, and $\nu^\sharp$ is the extreme value of $E(\nu)$ at (ν_0, ∞), when $E(\nu^\sharp)$ is extreme value, the minimum value of $E(\nu)$ is $E(\nu^\sharp)$. So the energy-minimization is $E(\nu^\sharp)$.

Due to $\nu^\sharp$ is the only stable point of $E(\nu)$ in the interval (ν_0, ∞), thus for any point of $\nu \in (\nu_0, \nu^\sharp) \bigcup (\nu^\sharp, \infty)$, there will be $E^{'}(\nu) \neq 0$. Furthermore, we confirm that $E^{'}(\nu)$ is different symbol at both ends of $\nu^\sharp$. If we assume $E^{'}(\nu)$ is same symbol at both ends of $\nu^\sharp$, there will be have two point $\nu_1, \nu_2 \in (\nu_0, \nu^\sharp) \bigcup (\nu^\sharp, \infty)$, which can be given as

$$E^{'}(\nu_1) E^{'}(\nu_2) < 0 \tag{23}$$

According to the Rolle theorem, we can get the existence a point $\nu_e \in (\nu_1, \nu_2)$, which make

$$E^{'}(\nu_e) = 0 \tag{24}$$

From the above formula, which is contradicts the existence of only one stable point. Obviously, $E(\nu)$ is strictly monotone in these two intervals. Therefore, $E(\nu^\sharp)$ is minimum value of UAV's energy, and $\nu^\sharp$ is the optimal solution to energy-minimization.

By simplifying the problem, we can get the following formula

$$E(\nu) = MR(\nu - \nu_0) + \frac{B + MR\nu_0^2}{\nu - \nu_0} + 2MR\nu_0 \tag{25}$$

Looking closely at the above formula, we found that the shape is like a check function. In order to further visualize the mathematical characteristics of the expression, we use $k = \nu - \nu_0$ to change the element. Through method of passing the mean inequality to address the problem.

$$MRk + \frac{B + MR\nu_0^2}{k} + 2MR\nu_0 \geq 2\sqrt{MRk \cdot \frac{B + MR\nu_0^2}{k}} + 2MR\nu_0 \tag{26}$$

When $MRk = \frac{B+MR\nu_0^2}{k}$, take the equal sign. So the energy of UAV is the minimum.

$$k = \sqrt{\frac{B + MR\nu_0^2}{MR}} \tag{27}$$

Therefore, the optimal solution to energy-minimization is

$$\nu^* = k + \nu_0 = \sqrt{\frac{B + MR\nu_0^2}{MR}} + \nu_0 \tag{28}$$

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