Communication-Aware Route Selection in Wireless Sensor Networks

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Abstract. We consider the problem of optimal route selection with the presence of path loss, multipath fading, interference, and environmental noise in wireless sensor networks. The communication-aware route selection strategy is proposed by incorporating realistic communication model portraying the underlying dynamics of wireless links. The link quality is characterized by probability of successfully received packets over a communication link, so-called reception probability. We utilize reception probability as a metric for communication quality oriented route selection and compare its performance with the conventional metrics i.e. Hop count and Euclidean distance. The simulation results demonstrate that reception probability based route selection provides optimal end-to-end throughput in wireless sensor networks.

1 Introduction

Recently, we have witnessed substantial interests in utilization of mobile platforms mounted with sensors and wireless modules for various applications such as rescue operations [3][4][5], target tracking [2], and environment observations [6]. Such systems are in general defined as mobile sensor networks, where mobile nodes perform two primary tasks: environmental data collection by self-navigation; data transmission through multihop wireless networks.

In the scope of this paper, we assume that mobile sensor nodes have reached their targets and collected environment exploited data through their sensing capacity. Collected information must be transferred to base station or peer nodes through self-organised ad hoc networks where nodes act as routers forwarding data through the selected route [7]. The quality of service in such networks primarily rely on reliability of wireless communication links constituting the route. Selecting optimal route with the highest quality of communication is the main objective of this paper.

The conventional route establishment schemes in multihop networks are based on simplified link models such as binary link model where nodes perfectly communicate within a transmission radius and nothing at all is communicated outside that radius [18]. Slightly refined approaches considers disk graph models where signal strength decays according to path loss and successful transmission is possible within a deterministic transmission radius [8] [9] [10]irrespective of wireless link conditions. These simplistic assumptions of disk models yields unrealistic inclusions with well documented limitations as explained in [1]. The route selection metrics based on such communciation models does not generate routes with high throughput in realistic scenarios as it neglects the sensitivity of wireless links in terms of noise, fading, and accumulated interference[11]. The Quality of Service (QoS) such as high throughput, and reliability is a crucial requirement for such multihop sensor networks.

In recent research trends, incorporating link quality with route selection has been considered. In [23], link quality estimation based routing protocol is proposed, which utilizes the link information recorded using the dynamic window concept. Sequential Assignment Routing (SAR) presented in [24] incorporates QoS in its routing decisions. However, such works do not consider the drastic effects of fading and Interference on the link quality.

In this paper, communication-aware route selection scheme is proposed to estimate the quality of realistic communication links using reception probability. This scheme utilizes reception probability as a route selection metric to search for a route with high end-to-end throughput in wireless sensor networks. We consider the inherent uncertainty of wireless communication link caused due to noise, interference, path loss and multipath fading. The integration of realistic communication model and route selection is necessary to realize the full potential of data communication in wireless sensor networks.

2 Conventional Route Selection Metrics

The routes for data communication are determined on the basis of route selection metrics. Most of the existing metrics such as hop count (HC) and Euclidean distance (ED) adapted for route selection are borrowed from ad hoc wireless networks . We examine the end-to-end throughput performance of such metrics in comparison with the proposed metric of reception probability (RP). The reception probability metric is presented in details in section 3.2.

2.1 Hop count(HC)

This metric is based on the concept of ideal communication link model i.e. either communication is perfect or there is no communication at all. The idea is to minimize number of hops on the route between a source and a destination. The implementation simplicity makes hop count the most widely used metric in ad hoc networks [20][21]. Its simplicity lies in the fact that computing the hop count does not require any additional measurements as compared to other metrics because hop count metric selects the optimal route with all the links with the same quality. However, in realistic scenarios the link quality varies, thus route selection based on hop count metric does not guarantee the most optimal route found because a route with more hops might provides better throughput [17].

2.2 Euclidean Distance (ED)

Geographical position is another popular approach for route selection in ad hoc wireless networks [22]. The usage of Euclidean distance (ED) as route selection metric requires that every node knows its physical position as well as positions of its neighbors. From the perspective of wireless link quality, this approach relies on disk graph models with only consideration of the path loss due to distance. ED-based route selection overlooks the fact that link quality can be dramatically changed over small distances by environmental noise, interference and multipath fading effects in indoor and urban environments.

3 Communication-Aware Route Selection

Considering a team of N mobile sensor nodes spatially distributed to jointly perform a task in a given environment, they have reached specific targets and each node requires sharing the information with all other nodes in the network. Note that we use the terms "node" and "router" interchangeably in this paper, in which node is used as general term for any nodes in the network while router is used for nodes on selected routes between a source and a destination. We assume that nodes remain static during the period of information sharing and each node has its own unique ID. There are more than one routes available for data transmission between a source and a destination. The objective is to find the optimum throughput routes to all destinations. The solution to problem of optimal route selection out of many available routes in realistic communication environment involves two steps:

- Find a suitable metric to represent link quality in realistic communication environment that take multipath fading, interference, and noise into account.
- Find optimal routes based on the selected metric.

3.1 Link Model

We assume a narrowband multipath fading wireless communication link. The link is modelled as the multiplicative Rayleigh flat fading with an additive white Gaussian noise (AWGN) process and large scale path loss exponent α [12]. Each transmitted signal reaches the destination via random number of multiple paths with no dominant line of sight (LOS) signal. The received signal is corrupted by M interference signals and AWGN noise process. The variance of noise process is denoted by N_o and P denotes the transmission power of all the nodes. The distance between a transmitter and a receiver is denoted by d_D and distance between an interferer and a receiver is denoted by d_m. Under the Rayleigh flat fading link model, the received power R and interference power I_m are exponentially distributed with $\bar{R} = P_o \left(\frac{d_D}{d_o}\right)^{-\alpha}$ and $\bar{I_m} = P_o \left(\frac{d_m}{d_o}\right)^{-\alpha}$ valid for $d_D, d_m > d_o$, respectively. d_o is the reference point located in far field of transmit antenna and P_o is the average power at d_o given as $P_o = P \left(\frac{\lambda}{4\pi d_o}\right)^{\alpha}$. The

Signal-to-Interference-and-Noise-Ratio (SINR) denoted by ζ, is a discrete random process given by:

$$\zeta = \frac{R}{N_o + I} \tag{1}$$

The SINR can be factorized into signal-to-interference-ratio (SIR) and signal-to-noise-ratio (SNR). For link between any two nodes i and j, SNR is the ratio of meant received power to meant noise power, given by $\zeta_{ij} = \frac{\bar{R}}{N_o}$ and SIR is the ratio of meant received power to meant interference power, given as $\zeta_m = \frac{\bar{R}}{I_m} = \left(\frac{d_D}{d_m}\right)^{-\alpha}$. The cumulative density function $F(\zeta)$ for SINR is given as [14]:

$$F(\zeta) = 1 - e^{\frac{-\zeta}{\zeta_{ij}}} . \prod_{m=1}^{M} \frac{1}{1 + \frac{\zeta}{\zeta_m}} \tag{2}$$

In order to mitigate the effects of interference, a slotted ALOHA scheme is used such that for each time slot, each node transmits independently with a certain transmission probability [15]. In (1) ,I is the accumulated interference power at a receiver given by $I = \sum_{m=1}^{M} B_m I_m$. The transmission probability p_t is assumed as a Bernoulli distribution such that B_m is a sequence of independent Bernoulli distributed random variable with $\mathbb{P}(B_m = 1) = p_t$ and $\mathbb{P}(B_m = 0) = 1 - p_t$.

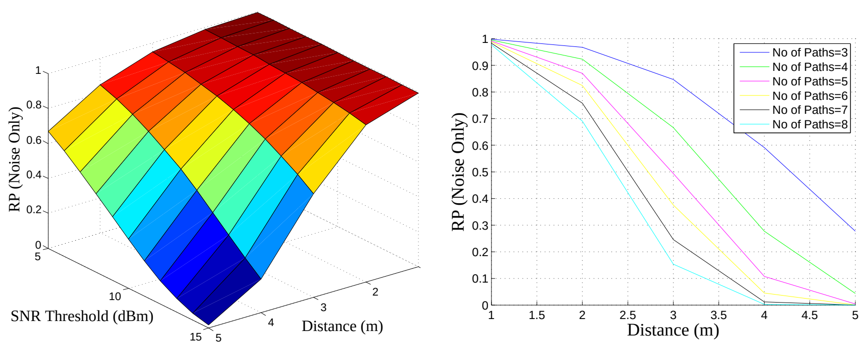
3.2 Reception Probability metric (RP)

The quality of wireless communication link can be determined by observing the instantaneous SINR(ζ) between two nodes. Generally, outage probability [13] is used to estimate the link quality and is defined as the probability that instantaneous SINR (ζ) falls below a certain threshold ζ_t. Consequently, a packet will be successfully received if $\zeta \geq \zeta_t$, the probability that instantaneous SINR between two nodes is high above a certain threshold ζ_t is called reception probability denoted by $p_r := \mathbb{P}[\zeta \geq \zeta_t]$. The value of ζ_t depends upon the modulation and coding sheme [19]. Reception probability of slotted ALOHA under Rayleigh fading channel is calculated using equation (2), and [16] shows that it can be factorized into reception probabilities of noise-only p_r^N, and interference-only p_r^I networks given as:

$$\begin{aligned}
p_r &:= \mathbb{P}[\zeta \geq \zeta_t] = 1 - F(\zeta) \\
&= exp\left(-\frac{\zeta_t}{\zeta_{ij}}\right) . \prod_{m=1}^{M} \frac{1}{1 + \frac{\zeta_t}{\zeta_m}} \\
&= exp\left(-\frac{\zeta_t N_o}{P_o \left(\frac{d_D}{d_o}\right)^{-\alpha}}\right) . \prod_{m=1}^{M} \left\{\mathbb{P}(B_m = 1) . \frac{1}{1 + \frac{\zeta_t}{\zeta_m}} + \mathbb{P}(B_m = 0)\right\} \\
&= exp\left(-\frac{\zeta_t N_o}{P_o \left(\frac{d_D}{d_o}\right)^{-\alpha}}\right) . \prod_{m=1}^{M} \left(\frac{p_t}{1 + \zeta_t \left(\frac{d_D}{d_m}\right)^{\alpha}} + 1 - p_t\right)
\end{aligned}$$

$$= \underbrace{exp\left(-\frac{\zeta_t N_o}{P_o\left(\frac{d_D}{d_o}\right)^{-\alpha}}\right)}_{p_r^N}\underbrace{\prod_{m=1}^{M}\left(1-\frac{p_t\zeta_t}{\zeta_t+\left(\frac{d_m}{d_D}\right)^{\alpha}}\right)}_{p_r^I} \quad (3)$$

The proposed scheme uses the Reception Probability (RP) given in (3) as route selection metric. This metric estimates the quality of realistic links with path loss, multipath fading, noise and interference effects. The metric is further investigated by simulating the behavior of p_r^N as a function of SNR threshold and distance between two nodes as shown in Fig.1(a). It is observed that p_r^N decreases as the distance between nodes increases. The results also show that reception probability is inversely proportional to the SNR threshold. Fig.1(b) shows the relationship between p_r^N and number of multipath in the link between nodes. It is noticed that reception probability decreases as the number of multipath increases between two nodes. The values assigned to parameters for obtaining these results are mentioned in Table.1.



(a) Distance (1-5m), SNR threshold (5-15 dBm)

(b) Number of multipath (3-8)

Fig. 1. Reception Probability (Noise Only).

3.3 Route Computation

All the routing schemes essentially rely on certain types of efficient shortest path algorithms such as Bellman-Ford or Dijkstras algorithm for route computation. These efficient algorithms are used to find the minimum weight routes based on given metric. In case of communication aware route selection, we need to find the route with the highest reception probability. The end-to-end reception probability for a route is the product of every independent reception probability of individual links comprising the route. After computing reception probability for each link, we take negative logs of these probabilities to turn multiplication of probabilities into addition of non-negative weights. Dijkstras algorithm is then used to compute the minimum weight routes which correspond to routes with the highest reception probability. The routes for HC-based and ED-based schemes are also computed using Dijkstras algorithm for comparison.

4 Performance Evaluation

The aim of our simulation is to evaluate the effectiveness of communication-aware route selection in finding optimal throughput routes. We also quantify the benefits of using RP as route selection metric over ED and HC for realistic communication model.

4.1 Performance measure:

Throughput is a conventional estimate for the amount of traffic delivered by the network [10]. We define the normalized throughput as the expected number of successful packet transmissions for a given node per time slot [17]. This normalized throughput can be thought of as fraction of time a channel is utilized. We consider end-to-end throughput over a multi-hop connection as the performance measure for a route. The end-to-end throughput for route is defined as the minimum of throughput values of the links involved in constituting the route. The throughput for each link between nodes i and j is given by:

$$TP\,(i,j) = p_t\,(1-p_t) \times p_r \tag{4}$$

Where p_r is the reception probability as given in equation (3), p_t is the probability that i transmits and $(1-p_t)$ is the probability that j does not transmit in the same time slot. The probability of transmission p_t in each time slot depends on the number of interferers on that particular link.

4.2 Simulation Setup

In all simulations, 200 nodes are randomly placed within a 50 by 50 (m) two dimensional square region. We make following operational assumptions underlying the development of proposed scheme: a) every node is static with has a unique ID, b) every node knows the relative distance to its neighboring nodes. The values selected for parameters in Table.1 to obtain numerical results for RP metric in equation (3) are representative of the real world low power wireless networks[25].

4.3 Results from illustrative scenarios

Simulation 1. One-to-All: We first consider the scenario shown in Fig.2, where a source node require routes to all other nodes in network. The node-91 is randomly picked as source node and routes to all other nodes are selected by applying three route selection metrics i.e. RP, ED, and HC.

Table 1. Values for parameters used in simulation

Parameter	Description	Value
P	Transmit Power	0 dBm
N_o	Noise Variance	-85 dBm
ζ_t	SINR Threshold	10 dBm
λ	Wavelength	0.12 m
α	Path loss exponent	4

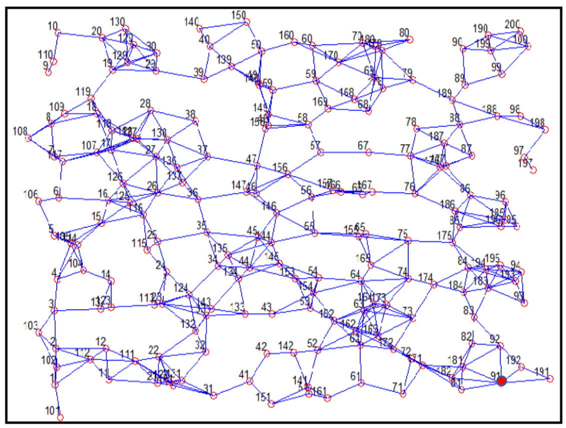
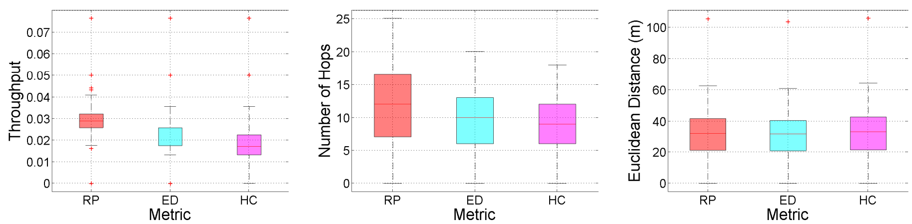


Fig. 2. Wireless network of 200 node with source node-91 (red), routes to all other nodes are selected using RP, ED, and HC metrics.

Fig. 3 compares the median end-to-end throughput, number of hops and euclidean distance for 199 routes selected from source node-91 to all other destination nodes in the network. We choose median to analyze the data instead of mean because the data distribution is quite skewed. In each box shown in fig 3 , the central mark represents median and difference between edges of the box represent the inter-quartile range (IQR). IQR is used to measure the dispersion of data and is defined as difference between 25th and 75th percentile of the data.

The median end-to-end throughput is 0.0289, 0.0175, 0.0170 for RP, ED and HC based routes respectively. The results show that routes selected using RP metric have higher throughput than routes found using conventional ED and HC metrics. In this typical case, RP-based route selection offers about 65% median throughput gain as compared to ED-based routes and 70% higher median throughput than HC-based routes. The median of the hops taken by RP, ED and HC based routes are compared in Fig. 3(b). Intuitively, the HC metric takes the minimum median of hops i.e 9 as compared to 10 for ED and 12 for RP-based routes. The routes selected by RP metric tend to comprise of more hops than either of the other metrics if each selected hop also provides higher throughput. The median Euclidean distance for all routes is slightly less for ED-based routes in comparison to RP and HC as shown in Fig. 3(c).



(a) Median Throughput

(b) Median Number of Hops

(c) Median Euclidean Distance

Fig. 3. Throughput, number of hops, and Euclidean distance for 199 source-destination routes

Simulation 2. One-to-One: We investigate a single source-destination case and analyze the route selection procedure for different metrics. The end-to-end throughput comparison is performed for RP, ED and HC-based routes selected for randomly chosen single source-destination pair (node-110-to-node-91) as shown in Fig.4.

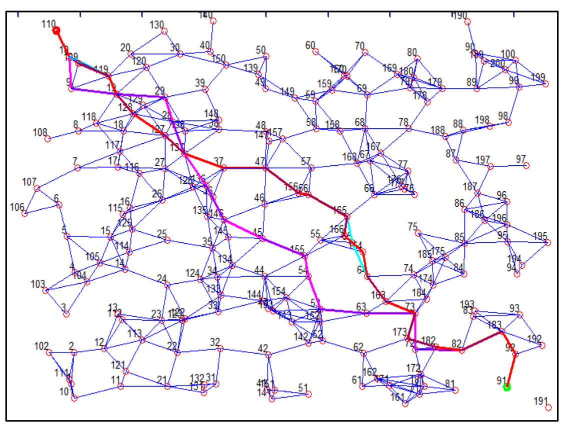
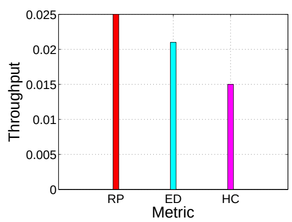
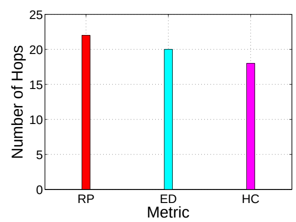


Fig. 4. Wireless network of 200 nodes with routes selected from source node-110(red) to destination node-91(green) using RP (red route), ED (cyan route) and HC (magenta route).

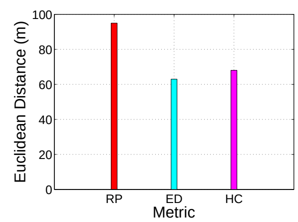
Fig.5(a) shows the achievable end-to-end throughput for the routes selected by each metric, RP metric outperforms the other two metrics. The end-to-end throughput of the route using RP metric is 0.025, while the routes based on ED and HC metric achieves 0.021 and 0.015 respectively. The end-to-end throughput gain for RP-based route is 20% and 66% more than ED and HC. Number of hops on each metric is presented in Fig.5(b). As expected, the HC metric chooses the shortest route between the source and the destination with lowest number of hops i.e. 18 but minimizing the hop count does not necessarily increase the throughput in realistic communication scenarios. Fig.5(c) shows that the RP-based route metric enables the longest distance while the ED-based route selection finds the route with minimum distance.



(a) End-to-end Throughput



(b) Number of Hops



(c) Euclidean Distance

Fig. 5. Throughput, Number of hops and Euclidean distance for a single source-destination pair

We observe in Fig.4 that other than two extra hops made by RP-based route; both RP and ED-based routes follow the same hops. The first extra hop comes very near to the source node where ED-based route goes directly from node-10 to node-119, whereas RP-based route makes an extra hop i.e. 10-109-119. The other extra hop occurs near the destination where ED-based route follows 165-65-64, while RP-based route takes the path of 165-166-164-64. In order to further investigate the reasons for these route diversions, we compare the reception probabilities (RP), throughput (TP) and Euclidean distances (ED) for these individual hops/links in Table 2.

Table 2. Comparison of RP, HC and ED(m) for selected hops on RP-based and ED-based routes.

Hops	10-119	10-109-119		165-65-64		165-166-164-64		
		10-109	109-119	165-65	65-64	165-166	166-164	164-64
RP	0.19	0.75	0.37	0.40	0.31	0.37	0.53	0.52
TP	0.021	0.120	0.046	0.045	0.034	0.060	0.065	0.064
ED(m)	3.824	1.098	2.753	2.799	3.907	2.048	2.358	2.655

In first route diversion for RP-based route, we observe that combined reception probability for 10-109-119 is 0.28 as compared to 0.19 for single hop case

10-119 in ED-based route. RP metric based route chooses the link with higher reception probability resulting in higher throughput. Similarly, in second diversion near the destination, ED-based route selection scheme chooses 165-65-64 because of the small combined distance of 6.70(m) as compared to 7.06 (m) for 165-166-164-64 chosen by RP-based scheme. RP-based scheme considers the stochastic nature of wireless links, whereas ED and HC based schemes select the route irrespective of condition and realization of wireless links.

Simulation 3. Dense Network: In order to further validate the proposed RP-based route selection scheme, we compare its performance with ED and HC in a much denser network where nodes are closely spaced and interference is high as shown in Fig.6. Node-195 is randomly picked as source with routes to all the other nodes in network. The median throughput, median number of hops and median euclidean distance for all the routes selected by different metrics are shown in Fig. 7. Results in the dense network provide evidence that RP-based

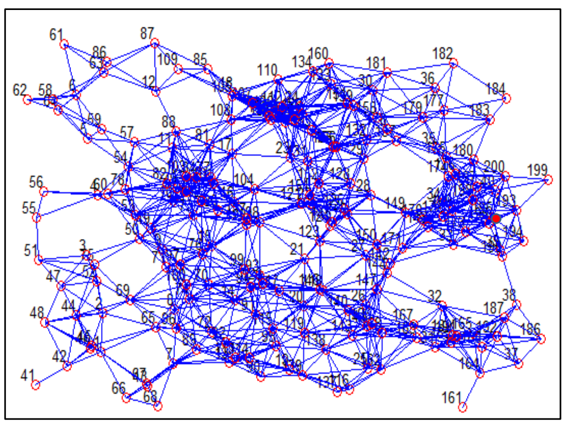
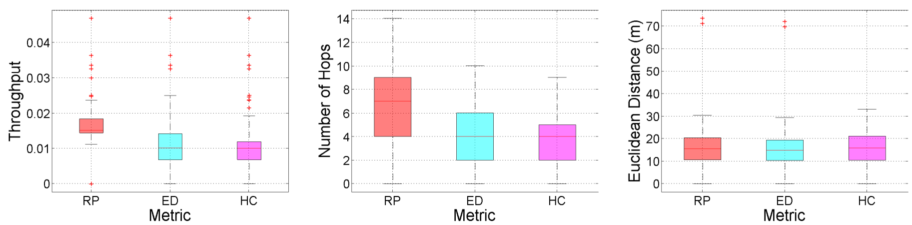


Fig. 6. Dense network of 200 nodes with source node-195(red), routes to all other nodes are selected using RP, ED, and HC.

routes surpasses the ED and HC based routes in terms of end-to-end throughput. Fig.7(a) shows that routes selected using RP provides a gain of about 50% in end-to-end median throughput as compared to the conventional metrics based on simplistic communication models. In dense networks, RP-based routes travels almost double number of hops i.e. 8, as compared to HC and ED (number of hops = 4) as seen in Fig.7(b). Intuitively, it seems that RP is higher at small distances but in reality it can be vice versa as it considers all the dynamics of wireless channel such as path loss, noise, interference and multipath fading. Fig.7(c) depicts that Euclidean distance for three metrics remains almost same in dense networks. The RP metric produces longer hops and travels more distance than both ED and HC metric but manages to provide higher throughput in realistic environment by considering the uncertainty of wireless links and choosing the high quality links with optimized throughput.



(a) Median End-to-End Throughput

(b) Median Number of Hops

(c) Median Euclidean Distance

Fig. 7. Throughput, Number of hops, and Euclidean distance for 199 source-destination routes in dense network

5 Conclusion and Future Work

It is crucial to achieve high throughput for ongoing data transmissions in wireless sensor networks, . We examined communication aware route selection scheme in presence of noise, path loss, multipath fading and interference. Reception probability is used to estimate link quality and select routes with higher end-to-end throughput. The performance is compared with conventional route selection schemes, hop count and Euclidean distance, using ideal link models. Simulation results exhibit that reception probability based route selection is the appropriate approach for achieving higher end-to-end throughput in wireless sensor networks.

Currently, we are working on the performance of proposed scheme with possibilities of node mobility. In future, the tradeoff between throughput and delay using reception probability metric will be analytically investigated.

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