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A Conceptualized Model for Data Transmission in Underwater Acoustic Wireless Sensor Network

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Abstract: The complexity of underwater acoustic channel is considered to be quite possibly nature's most unforgiving wireless medium. Nodes in underwater sensor networks which are used for oceanographic data collection, pollution monitoring, offshore exploration, tactical surveillance applications, and rapid environmental assessments are constrained by harsh physical environment. Also, data delivery schemes originally designed for terrestrial sensor networks are unsuitable for use in the underwater environment. Hence, this work investigates the development of an underwater transmission model by proposing a conceptualized Model for Data Transmission in Underwater Acoustic Wireless Sensor Network. The work assume that the noise power is the same for all the links. The work also assumes the channels are stable over each transmission frame. Without the relay nodes, the proposed mathematical model presents the minimum possible transmit power to achieve the required data rate between transmitting node and relay node. It evaluates the proposed model, after conducting several trials under different operating conditions using the data obtained. It then shows Throughput against Channel Bandwidth. Data transmission rate which can be measured from the graph shows an increase in channel bandwidth with decrease in throughput. Results show that at optimal power the proposed transmission model has significant advantages of improved performance and robustness over both the traditional direct transmission and the existing cooperative transmission schemes.

Keywords: Acoustic; Data transmission; Throughput; Underwater acoustics sensor network; Wireless sensor network.

1. INTRODUCTION

Underwater acoustic communications have been attracting growing interest in the past three decade because of its applications in marine research, oceanography, marine commercial operations, the offshore oil industry and defense. Efficient underwater communications are critical to many types of scientific and civil missions in the ocean, such as ocean monitoring, ocean exploration, undersea rescue, and undersea disaster response. Human knowledge and understanding of the oceans, rests on our ability to collect information from remote undersea locations. Together with sensor technology and vehicular technology, wireless underwater communications are desirable to enable new applications ranging from environmental monitoring to gathering of oceanographic data, marine archaeology, and search and rescue missions [1]. There is no arguing the fact that a huge amount of unexploited resources lies in the 75% of the earth covered by oceans. However, the aquatic world has mainly been unaffected by the recent advances in the area of Wireless Sensor Networks (WSNs) and their pervasive penetration in modern day research and industrial development. This current slow pace of research in the area of Underwater Acoustic Sensor Networks (UASNs) is due to the difficulties arising in transferring most of the land and air based WSNs [2]. Terrestrial and airborne WSNs rely on radio frequencies as their communication medium for transmitting data and information, sensing and subsequent transmission in sub-sea environment requires all together a different approach for communication that has to be done underwater. Nodes in underwater sensor networks which are used for oceanographic data collection, pollution monitoring, offshore exploration, tactical surveillance applications, and rapid environmental assessments are constrained by harsh physical environment. Also, data delivery schemes originally designed for terrestrial sensor networks are unsuitable for use in the underwater environment [3].

Underwater acoustic channels are considered to be quite possibly nature's most unforgiving wireless medium [4]. This is why the building of an efficient UWSN for underwater wireless communication is very challenging. High Frequency (HF) radio waves are strongly attenuated in water. The available radio modules such as Bluetooth or Wireless LAN (IEEE 802.11),

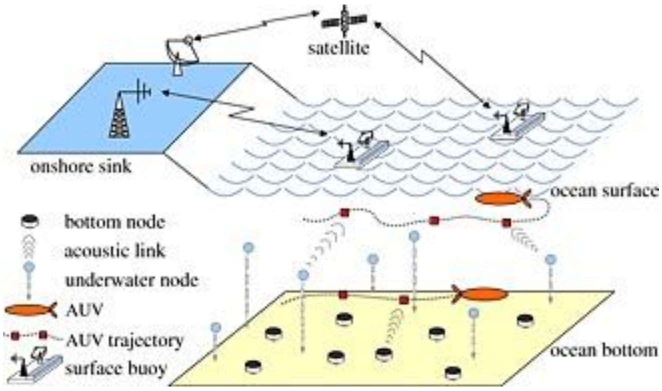

Figure 1. A three-dimensional mobile underwater acoustic sensor networks architecture. AUV, autonomous underwater vehicles [3,6]

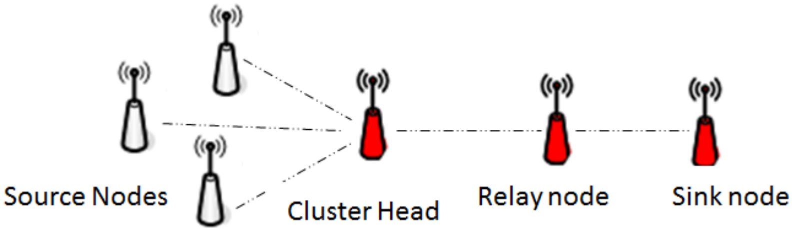

Figure 2. Node arrangement for underwater Acoustic Wireless Sensor Network

which operate in the gigahertz range, around 2.4 GHz, cannot be used underwater where, currently, acoustic communication is mainly employed [2]. Figure 1 shows a three-dimensional mobile underwater acoustic sensor networks architecture. The complexity of underwater acoustic channels is dominated by the ocean environment characteristics which include significant delay, double-side-spreading, Doppler-spreads, frequency-selective fading, and limited bandwidth [5].

Moreover, underwater acoustic channels normally have low data rates and time-varying fading. These factors determine the temporal and spatial variability of the acoustic channel and make the available bandwidth of the ocean channel both limited and dependent on range and frequency. Challenges due to the presence of fading, multipath, and refractive properties of the sound channel necessitate the development of precise underwater-channel models. Some existing channel models are simplified and do not consider multipath or fading. Multipath interference due to boundary reflection in shallow-water acoustic communications poses major obstacles to reliable high-speed underwater communication systems [7].

Continued research over the years has resulted in improved performance and robustness in underwater communication systems. However, relatively few new schemes have been proposed for underwater use, but no single scheme has yet emerged as the de facto standard. One of such transmission technique is Cooperative transmission, a new wireless communication technique in which diversity gain can be achieved by utilizing relay nodes as virtual antennae [8]. Hence, the aim of this work is to investigate the development of an underwater transmission model using cooperative transmission for improved performance and robustness [3].

2. METHODOLOGY

In this paper we research on developing a transmission model for UWASN based on Acoustic Wireless Sensor network communication by employing the amplify-and-forward (AF) cooperation protocol [9] as our system model; in which there are total *N* relay nodes, one source node *s* and one destination node and other relay nodes [1,10]. Also, we advance a collaborative spectrum sensing method based on Stackelberg game [11] and cooperative Collaborative game theory [9] for underwater acoustic node arrangement and data transmission as shown in Figure 2.

It involves studying the performance of several cooperative transmission schemes for underwater scenario. Secondly, designing a new wave cooperative transmission scheme in which the relay nodes amplifies the signal received from the source node and then forward the signal immediately to the intended destination by taking advantage of the relatively low propagation speed of sound in water. The goal is to alter the multipath effect at the receiver. Thirdly, derive the optimal performance for the proposed wave cooperative transmission scheme.

3. DATA TRANSMISSION MODEL FOR UASN

Source node s broadcasts its information to both destination node d via relay node r_i. The received signals ys, d and ys, r_i at node d and node r_i can be expressed as

$$ys, d = \sqrt{Q_s\, G_{s,d^x} + \eta_{s,d'}} \tag{1}$$

$$mys,r_i \;=\; \sqrt{Q_s\, G_{s,r_i} x + \,\eta_{s,r_i}} \tag{2}$$

where Q_s represents the transmit power at node s, x is the broadcast information symbol with unit energy from node s to node d and node r_i, $G_{s,d}$ and $G_{s,ri}$ are the channel gains from node s to node d and node r_i respectively, and $\eta_{s,d}$ and $\eta_{s,ri}$ are the additive white Gaussian noises. Without loss of generality, we assume that the noise power is the same for all the links, denoted by σ^2 given that channels are stable over each transmission frame [2]. We assume the channels are stable over each transmission frame. Without the relay nodes' help, the signal-to-noise ratio (SNR) that results from the direct transmission from node s to node d can be expressed by

$$SNR_{s,d} = \frac{Q_s\, G_{s,d}}{\sigma^2} \tag{3}$$

and the rate of the direct transmission is

$$R_{s,d} = F1og_2\left(1 + \frac{SNR_{s,d}}{K}\right) \tag{4}$$

where F is the bandwidth for transmission, and K is a constant representing the capacity gap., relay node r_i amplifies $y_{s,ri}$ and forwards it to destination d with transmitted power Q_{ri} . The received signal at destination node d is

$$y_{r_i,d} = \sqrt{Q_{r_i}\, G_{r_i,d} x_{r_i,d} + \eta_{r_i,d}} \tag{5}$$

where

$$x_{r_{i,d}} = \frac{ys,r_i}{ys,r_i} \tag{6}$$

is the transmitted signal from node r_i to node d that is normalized to have unit energy, $G_{ri,d}$ is the channel gain from node r_i to node d, and $\eta_{r_{i,d}}$ is the received noise. Substituting Equation (2) into Equation (6), we can rewrite Equation (5) as

$$Y_{r_i,d} = \frac{\sqrt{Q_{r_i}\, G_{r_i,d}(\sqrt{Q_s\, G_{s,r_i} x^{+}\, \eta_{s,r_i})}}}{\sqrt{Q_s\, G_{s,r_i} + \sigma^2}} + \eta_{r_{i,d}} \tag{7}$$

$$SNR_{s,r_i,d} = \frac{Q_{r_i}\, Q_s\, G_{r_{i,d}} G_{s,r_i}}{\sigma^2 (Q_{r_i}\, G_{r_{i,d}} + Q_s G_{s,r_i} + \sigma^2)} \tag{8}$$

Therefore, by using Equations (4) and (8), we have the rate detector at the output as

$$R_{s,r_i,d} = \frac{F}{2}\log_2\left(1 + \frac{SNR_{s,d} \;+\; SNR_{s,r_i,d}}{K}\right) \tag{9}$$

$$R_{s,r,d} = \gamma_L F \log_2\left(1 + \frac{SNR_{s,d} + \sum r_i \in l(SNR)_{s,r_i,d}}{K}\right) \tag{10}$$

where γ_L is the bandwidth factor. The source nodes can be modelled as a packet transmitter. Let the utility function of source nodes can be defined as

$$U_s = \mu R_{s,r,d} - T \tag{11}$$

U is ability for the node to receive and transmit and $R_{s,r,d}$ denotes the achievable rate with the relay nodes' help, μ denotes the gain per unit of rate at the T output of all nodes [5, 6]

$$T = \sum_{r_i EL} q_i\, Q_{r_i} = q_1 Q_{r_i} + \; q_2\, Q_{r2} + \; \ldots + \; q_N Q_{rn} \tag{12}$$

T represents the total relay tendencies by node s to the relay nodes. In Equation (12), q_i represents the data from relay node r_i to source node s, and Q_{ri} denotes how much power node s to transmit to next relay node. The relay nodes constitute a set denoted by the length or number of relay nodes, L can be formulated as

$$max\, U_s = \mu R_{s,r,d} - T, s.t. Q_{r_i} \geq 0, r_i \;\in L \tag{13}$$

$$U_{ri} = q_i Q_{r_i} - o_i Q_i = \left(q_{i-o_i}\right) Q_{r_i} \tag{14}$$

where o_i represent received data.

$$max\ U_{r_i} = (q_{i\ -o_i})\ Q_{r_i},\ \forall i \tag{15}$$

4. RELAY SELECTION

As relay nodes are located in different places and data is transmitted and received from one node to the other [2], we can maximize utility U_s through matching an optimal amount of power P_{ri}. Then a natural way of relay selection for source node s is to observe how U_s varies with Q_{ri}, i.e., observe the sign $\partial U_s/\partial Q_{ri}$. Since source nodes gradually changes in the power with sequence of transmission, by observing the sign $\partial U_s/\partial Q_{ri}$ of when $Q_{ri} = 0$, node s can exclude (or select) those less (or more) beneficial relay nodes.

4.1 Optimal Power Allocation for Relay Nodes

After the selection, for the selected relay nodes that constitute a set $L_h = \{r_1, \cdots, r_N\}$, we can solve the optimal power Q_{ri} by taking derivative of U_s in Equation (11) with respect to Q_{ri} as

$$\frac{\partial U_s}{\partial Q_{ri}} = \mu \frac{\partial R_{s,r,d}}{\partial Q_{ri}} - Q_i,\ i = 1,\ \ldots, N. \tag{16}$$

$$\frac{\partial U_s}{\partial Q_{ri}} = \mu \frac{\partial R_{s,r,d}}{\partial Q_{ri}} - Q_i = 0, r_i \in L_{h.} \tag{17}$$

$$aR_{s,r,d} = \pi r^2\ \mu W \log_2(1 + \textstyle\sum_{ri\ \in L_h} SNR_{s,r_i,d\,=}\ F \ln(1 + \Delta SNR'_{tot}) + F \ln C \tag{18}$$

where

$$\Delta SNR_{tot} = 1 + \sum_{ri\ \in L_h} SNR_{s,r_i,d} = \frac{1}{KC} \sum_{ri \in L_h} SNR_{s,r_i,d} \tag{19}$$

$$SNR_{s,r_i,d} = \frac{SNR_{s,r_i,d}}{KC} = \frac{H_i}{1+\frac{E_i}{Q_{r_i}}} = \frac{H_i\, Q_{r_i}}{Q_{r_i}+E_i} \tag{20}$$

with $H_i = \frac{Q_s\, G_{s,r_i}}{(K\sigma^2+Q_s G_{s,d})}\ and\ E_i = \frac{Q_s\, G_{s,r_i}+\sigma^2}{G_{r_i,d}}$.

By substituting Equations (12) and (18) into Equation (17), we have

$$\frac{F\prime}{\left(1+ \sum\limits_{r_i \in L_h} \frac{H_k P_{rk}}{F_{rk}+E_k}\right)} = \frac{p_i}{H_i E}\ (Q_{r_i} + E_i)^2 \tag{21}$$

and

$$Q_{r_i} = \sqrt{\frac{q_{r_i}\, H_i\, E}{q H_i E_i}}\ (Q_{ri} + E_i) \tag{22}$$

By substituting Q_{rj} into Equation (20) and simplifying, we have

$$SNR_{s,r_i,d} = \frac{H_j}{1+\frac{E_j}{Q_{rj}}} = H_j - \sqrt{\frac{q_j H_i E_i}{q_j H E_i}}\ \frac{H_j\, E_j}{(Q_{ri}+E_i)} \tag{23}$$

Then Equation (19) can be reorganized as

$$\begin{aligned} \Delta SNR_{tot} &= \left[H_1 - \sqrt{\frac{q_1 H_i E_i}{q_i A_1 B_1}}\ \frac{H_1 E_1}{(Q_{ri} + E_i)}\right] + \ \ldots + \left[H_i - \frac{H_i E_i}{Q_{ri} + E_i}\right] + \left[H_N - \sqrt{\frac{PN'^{H_i E_i}}{q_i H_N E_N}}\ \frac{H_{NE_N}}{(Q_{ri} + E_i)}\right] \\ &= \sum H_j - \sqrt{\frac{H_i E_i}{q_i}} \frac{1}{Q_{r_i} + E_i} \sum_{r_{j \in L_h}} H_i - \sqrt{\frac{H_i E_i}{q_i}}\ \frac{1}{Q_{r_i} + B_i} \sum_{r_{j \in L_h}} \sqrt{q_j H_j E_j} \end{aligned} \tag{24}$$

By substituting Equation (24) into (21), we can have a quadratic equation of Q_{ri}. The optimal power consumption now becomes

$$Q_{ri}^{*} = \sqrt{\frac{H_i E_i}{p_i}}\ \frac{Y + \sqrt{Y^2+4XF}}{2\,X} - E_i \tag{25}$$

where $X = 1 + \sum r_{j \in L_h} H_j$ and $Y = \sum r_{j \in L_h} \sqrt{(q_j H_j E_j)}$, since the U_s function is concave in $\{Q\}^N{}_{i=1}$ and the supporting set $\{Q_{ri} | Q_{ri\}} \geq 0, i = 1, \cdots, N\}$ is convex.

$$max\, U_{ri} = (q_i - o_i) q_{ri}^* \,(q_{1,\dots,} q \ldots q_{N'}). \quad \{q_i\} >_0 \tag{26}$$

$$\frac{\partial U_{ri}}{\partial q_i} = Q_{ri}^* + (q_i - o_i) \frac{\partial Q_{ri}^*}{\partial q_i} = 0, r_{i \in L_h} \tag{27}$$

Solving the above equations of q_i, we denote the optimal data transmission as

$$q_i^* = q_i^* \left(\sigma^2, \{G_{s,ri}\}, \{G_{ri,d}\}\right), r_{i \in L_h} \tag{28}$$

5. RESULTS AND DISCUSSIONS

Based on the concept, the proposed mathematical model presents the minimum possible transmit power to achieve the required data rate between transmitting node and relay node. In order to evaluate the proposed model, we conducted several trials under different operating conditions using the data obtained.

In Figure 3, Throughput was plotted against Packet Size. Data transmission rate can be measured from the graph and this shows an increase in Packet size with decrease in throughput. Figure 4 shows throughput against bit rate where there is a significant increase in throughput with respect to increasing bit rate. Figures 5 and 6 show energy per bit against channels and number of carriers. The energy per bit decreases with increase in channel bandwidth in Figure 3, while energy per bit increases with increase in number of sub-carriers as shown in Figure 4.

5.1 Performance Evaluation

Performance evaluation was carried out as show in Table 1 using Mean Squared Error (MSE) or mean squared deviation (MSD) of an estimator (of a procedure for estimating an unobserved quantity) which measures the average of the squares of the errors. This is the average squared difference between the estimated values and what is estimated. MSE is a risk function, corresponding to the expected value of the squared error loss.

$$\text{MSE} = \frac{I}{n} \sum_{i=1}^{n} (Y_i - Y_p)^2 \tag{29}$$

where Y_i is the value of Actual data of Packet Size and Y_P is the value of Predicted data of Packet Size.

$$\text{MSE} = \frac{I}{n} \sum_{i=1}^{n} (Y_a - Y_b)^2 \tag{30}$$

where Y_a is the result from the data collected from the field and Y_b is the result from the data from the model. In this case MSE = 6.905×10^{-9} is obtained as shown in Table 1. MSE has better performance in measuring error since it takes the mean of all the deviation. The result shows that the deviation was minimal which also indicate that the model performed better. The graph in Figure 7 is a comparison between the actual and predicted output. The results between the simulated and actual outputs are shown.

Table 1. Values of the actual and predicted data of packet size

n	Packet size	Actual value of packet size (Y_i)	Predicted value of packet size (Y_P) $\times 10^{-2}$	($Y_i - Y_P$) $\times 10^{-5}$	$(Y_i - Y_P)^2 \times 10^{-9}$
1	50	0.16	16.0020	2.0	0.400
2	75	0.13	13.0038	3.8	1.444
3	100	0.10	10.0210	21.0	44.100
4	130	0.09	9.0020	2.0	0.400
5	160	0.08	8.0017	1.7	0.289
6	175	0.07	7.0120	12.0	14.400
7	200	0.06	6.0017	17.0	0.289
8	225	0.05	5.0016	1.6	0.256
9	250	0.04	4.0013	1.3	0.169
10	275	0.03	3.0002	0.2	0.004
11	300	0.02	2.0090	9.0	8.100
				$\sum (Y_i - Y_P)^2 = 69.05 \times 10^{-9}$	

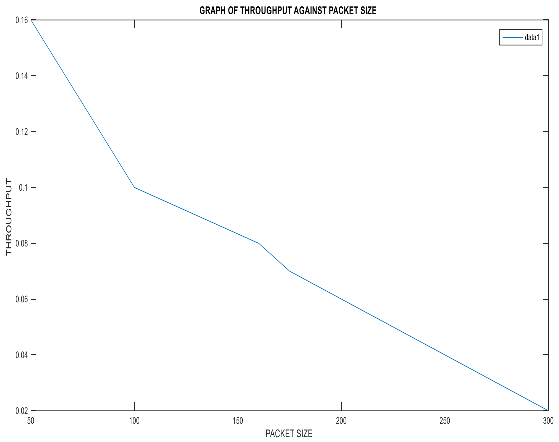

Figure 3. Throughput against Packet size

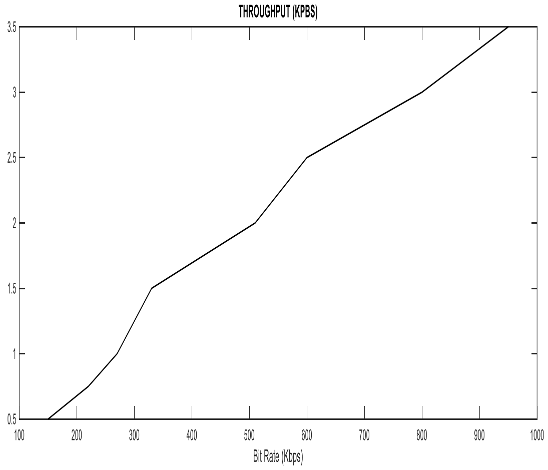

Figure 4. Graph of Throughput against bit rate

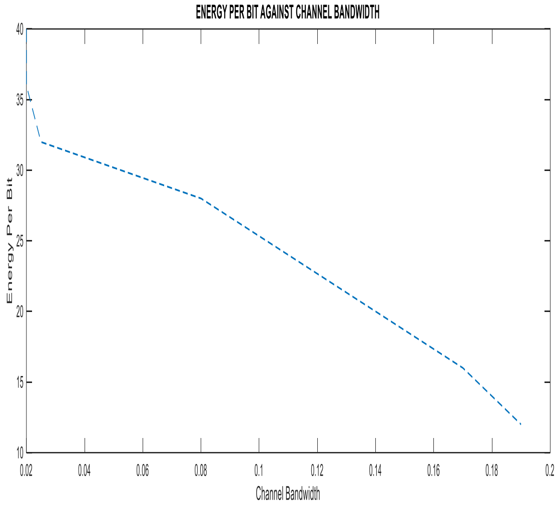

Figure 5. Energy per bit against channel bandwidth

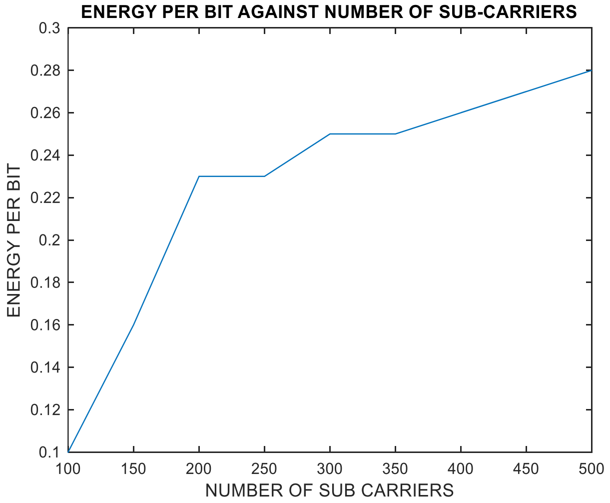

Figure 6. Energy per bit against number of sub-carriers

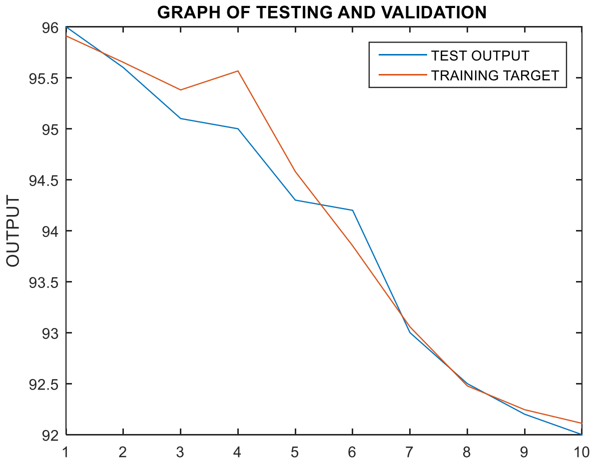

Figure 7. Graph of comparison between the original data and simulated data

6. CONCLUSION

This paper explored the complexity of underwater channel by deriving and developing a proposed model for data transmission for underwater acoustic channel at optimal power. It considered the transmitted power and channel putting into consideration noise power as the same for all links. The work shows that there is an increase in channel bandwidth with decrease in throughput. The work also establishes that there is a significant increase in throughput with respect to increasing bit rate. Figures 5 and 6 show energy per bit against channels and number of carriers decreases with increase in channel bandwidth. Given that the channels are stable over each transmission frame, we then evolve a direct transmission between source node and relay node, which shows that at optimal power, the proposed transmission model has significant advantages of improved performance and robustness over both the traditional direct transmission and the existing cooperative transmission schemes.

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