Simulating the Performance of SW-ARQ Schemes within Molecular Communications

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Abstract

This paper provides results on an investigation concerning the application of five tailored Stop-and-Wait Automatic Repeat reQuest (SW-ARQ) schemes to a diffusion based molecular communication system. Each scheme is numerically simulated and evaluated to determine its performance with regards to average time cost and energy consumption. It is shown that all five schemes are beneficial depending upon the application scenario. Scheme 1 is the best choice for adjacent communications although, if a slightly higher energy budget can be afforded, schemes 2 and 3 will provide better performance than scheme 1 as the communication distance increases. Schemes 4 and 5 are designed to benefit scenarios with either a varying channel or for a channel with unknown parameters although will also benefit a static channel if again, further system energy can be utilised. This optimisation and trade-off between time and energy requirement for a complete successful transmission will become more important in future applications involving molecular communications where energy efficiency is a design consideration.

Keywords: Molecular Communications, Nanonetworks, SW-ARQ

1. Introduction

The Stop-and-Wait Automatic Repeat reQuest (SW-ARQ) scheme is a method in traditional communications to ensure that information packets are transmitted successfully between two connected devices[1, 2]. The communication system using the SW-ARQ scheme requires a two-way channel: one for the information or payload packet transmission, and the other for the acknowledgement (ACK) packet transmission. With the help of the ACK packet, the transmitter can know whether the payload packet is transmitted successfully. However, this scheme has drawbacks, namely, the reduction of the transmission rate due to the delay caused by the retransmission, and an increase in complexity.

To enable a complete communication framework within molecular- or nano-communications, it is required that various primitives be combined to define the protocol abstraction [3, 4]. In [5], an example of such an abstraction, named Assured State Transfer, was mentioned. Similar to the SW-ARQ scheme in macro-communications applications, Assured State Transfer is designed to enable the reliable transmission of signalling molecules from the source to the destination. As is shown in Fig. 1, the procedure of this protocol abstraction is as follows. First, the molecules, or bio-molecules, which have been encoded with both the message and the index [6, 7] (represented as S1), are emitted by the transmitting (Tx) nanomachine and propagate to the receiving (Rx) nanomachine. Upon reception, the S1 molecules stimulate Rx to release another type of molecules or bio-molecules, known as ACKnowledgements or ACKs (represented as S2). When S2 are received by Tx, they stimulate the nanomachine to stop releasing S1. In this way, this protocol abstraction guarantees that no more S1 are transmitted to Rx, thus attempting to make each state more reliable.

Further work on the Assured State Transfer protocol abstraction was carried out in [6, 8] where simulations on a molecular based reliable communication protocol with nano-logic computation were discussed. In [9], we expanded the idea and investigated three schemes, schemes 1 through 3 in this paper, but most results were simulated with only two fixed values of the pre-designed waiting time (T_r), and averaged after only 5000 retrails. In this paper, we have further enhanced the abstraction, proposing five schemes, and combined it with a realistic physical end-to-end model. The work here has gone beyond our work in [9] with the inclusion of two additional 'adaptive' schemes along with further results in the parameters for the first three schemes. Furthermore, we have increased the number of re-trials to 15000 in order to enhance the reliability of the results.

The remainder of this paper is organized as follows. In Section 2, the communication model and the system structure are introduced. The transmission schemes are explained in Section 3. Simulations and comparison of results are provided in Section 4 for each scheme. Finally, in Section 5, we conclude the paper.

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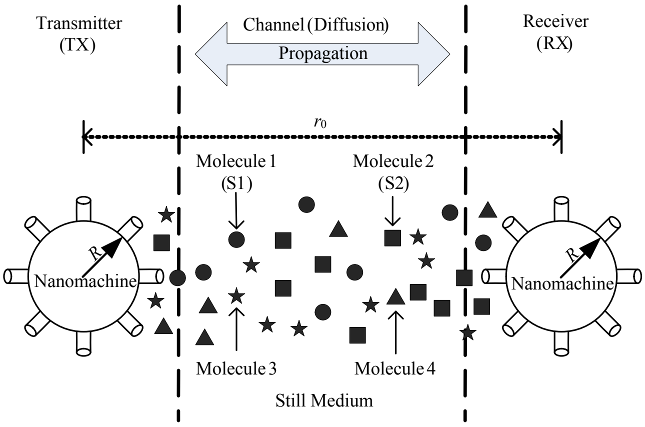

Figure 1: The micro- or nano-communication system considered.

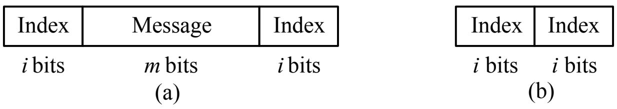

Figure 2: The structure of: (a) The transmission packet. (b) The ACK.

2. The System Model

The focus of this work is to present how the use of SW-ARQ schemes can benefit a micro- or nano-communications system. For the purposes required herein, and as shown in Fig. 1, the system consists of two nanomachines acting in a way that is analogous to biological entities [10]. One nanomachine, acting as a transmitter, Tx, communicates to the receiver, Rx, via the diffusion of uniquely identifiable transmission molecules [11], such as those encoded via a natural ligand-receptor binding mechanism [12]. It is further assumed that the molecules used to transmit packets with index I do not interfere with molecules for the corresponding ACKs with index I (otherwise known as pheromone diversity [13]). The structure of the packets is shown in Fig. 2, whereby it can be seen that a transmission packet, consisting of m message bits is adjoined by two pairs of i index bits, and that the corresponding ACK consists purely of two pairs of the i index bits. Based upon this desciption, it can be noted therefore, that I ranges from between 0 to $2^i - 1$.

The medium is assumed to be a diffusing channel [14, 15] where the molecules have a capture probability $P(r_0, t)$ given by[16, 17]:

$$P(r_0, t) = \frac{R}{r_0} \text{erfc} \left\{ \frac{r_0 - R}{2\sqrt{Dt}} \right\}, \tag{1}$$

where, with reference to Fig. 1, R is the effective capture radius of Rx (or Tx), in μm, r_0 is the distance between the nanomachines, in μm, D is the diffusion coefficient, in $\mu\text{m}^2\text{s}^{-1}$, and t is time in s. In this paper, $R = 5\mu$m and $D = 79.4\mu\text{m}^2\text{s}^{-1}$, a conservative value for insulin in water at the human body temperature [18].

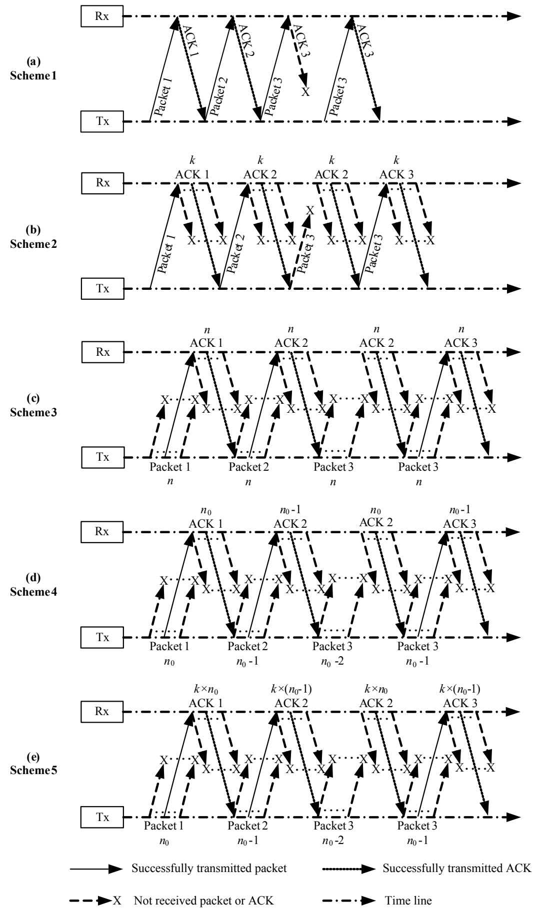

Figure 3: The five proposed Stop-and-Wait Automatic Repeat reQuest (SW-ARQ) schemes.

3. The SW-ARQ Schemes

Five schemes are considered in this work as shown in Fig. 3.

3.1. Scheme 1

This is similar to the traditional SW-ARQ scheme. As shown in the Fig. 3(a), the Tx transmits a packet and waits for the ACK from the Rx. If the waiting time is longer than a pre-defined limit, T_r, the Tx retransmits the packet. When receiving the packet, the Rx sends back an ACK and waits for the next packet from the Tx. If the waiting time is longer than the same pre-defined limit, the Rx retransmits the ACK.

This scheme enjoys great simplicity but suffers from high rate of unsuccessful transmission, especially for long range communications. This has limited the application of this scheme to a very narrow area: adjacent range communications. For example in the biomedical field [5], new smart drug delivery systems are designed to combine the sensing capabilities of nanomachines with the abilities of nano-actuators to release specific drugs inside the body. The communication between these two kinds of adjacent nanomachines could be fulfilled using this scheme. In this scenario, this scheme will be both simple and reliable.

3.2. Scheme 2

This scheme, as shown in Fig. 3(b) is based on the traditional SW-ARQ scheme. But when the Rx receives a packet, it sends back k copies of the corresponding ACK simultaneously, where k is an integer value given by:

$$k = \frac{\text{Number of ACKs sent in a single transmission}}{\text{Number of packets sent in a single transmission}} \tag{2}$$

As soon as at least one of the k ACKs is received by the Tx, the next packet will be transmitted. Then the probability of a successful complete transmission of the wanted packet can be derived, that is:

$$P_k = P(r_0, t) \times (1 - (1 - P(r_0, t))^k) \tag{3}$$

Based on the structures shown in Fig. 2, a length ratio l is defined as the ratio of the length of the packets and the ACKs, that is,

$$l = \frac{\text{The length of the packets}}{\text{The length of the ACKs}} = \frac{m + 2i}{2i} = 1 + 2\frac{m}{i}, \tag{4}$$

which implies that for large l (which means the length of the ACKs is significantly smaller than that of the packets), when a packet does arrive at Rx, but the corresponding ACK is lost, this scheme will use less energy compared to scheme 1.

3.3. Scheme 3

When the distance between the Tx and the Rx is quite large, the capture probability is known to be low [15], leading to a high probability of re-transmission. This will potentially cost too much time and energy. To solve this problem, in this scheme, as shown in Fig. 3(c), the Tx simultaneously sends n copies of the current packet, and as soon as at least one of these copies is received, the Rx will send back n copies of the corresponding ACK. Incorporating the capture probability of one packet (or ACK) as expressed by equation (1), the probability of a successful complete transmission of the wanted packet is given by:

$$\begin{aligned} P_n &= (1 - (1 - P(r_0, t))^n)) \times (1 - (1 - P(r_0, t))^n) \\ &= (1 - (1 - P(r_0, t))^n)^2 \end{aligned} \tag{5}$$

For $n = 1$, P_n is the probability of a successful complete transmission using scheme 1, that is, $P_1 = P(r_0, t)^2$. It is therefore obvious that $P_n >> P_1$ when n is large. In this way, if n is properly selected, the time cost will be reduced greatly with no significant increase in energy. This scheme has relatively higher rate of successful transmission, but it is more complex than schemes 1 and 2, which requires the nano-machines to have higher complexity. The application of this scheme lays on long range communications, where a higher power budget may be envisioned.

3.4. Scheme 4

This scheme is based on scheme 3 and the scheme proposed in [19]. As is shown in the Fig. 3(d), the procedure of transmission is: $n_p^{(j)}$ is defined as that the Tx transmits $n_p^{(j)}$ copies of the I^{th} packet for the j^{th} transmission of the whole procedure, and $n_a^{(j)}$ is defined as that the Rx transmits $n_a^{(j)}$ copies of the corresponding ACK for the j^{th} transmission of the whole procedure. For the first transmission, that is $j = 1$, $n_p^{(1)} = n_a^{(1)} = n_0$. If the number of copies of current packet being transmitted is given as $(n_p^{(j-1)} + n_p^{(j-2)} + n_p^{(j-3)} + \cdots)$, when at least one of the $(n_p^{(j-1)} + n_p^{(j-2)} + n_p^{(j-3)} + \cdots)$ packets is transmitted successfully, the Tx will send $n_p^{(j)} = n_p^{(j-1)} - 1$ copies of the next packet; when all of the $(n_p^{(j-1)} + n_p^{(j-2)} + n_p^{(j-3)} + \cdots)$ packets fail to transmit, the Tx will send $n_p^{(j)} = n_p^{(j-1)} + 1$ copies of the current packet. A parallel situation occurs in the Rx with regards to the number of the copies of the ACK. This procedure will continue until all the packets have been transmitted successfully. With sufficient packets to be transmitted, the number of copies of the packets (or ACKs) will be adaptively altered around a certain value, which could be the optimal number of the copies. If the distance between the Tx and the Rx is large, based on the equation (5), it is obvious that the value of P_{n-1} is close to the value of P_n with small $P(r_0, t)$ but with accumulation there will be huge differences, such as $P_{10} >> P_1$. Thus within long range distance communications, scheme 4 has great superiority due to the 'adaptivity' of the system for a channel with unknown suitable number of copies to guarantee the successful transmission probability without much redundant energy consumption.

3.5. Scheme 5

This scheme, as shown in Fig. 5(e), is a combination of scheme 2 and scheme 4. When Tx transmits n packets for a trial, the Rx will transmit $k \times n$ ACKs, where k is an integer value as given by (2).Then the probability of successful transmission of the wanted packet is obtained by:

$$P'_{n,k} = (1 - (1 - P(r_0, t))^n) \times (1 - (1 - P(r_0, t))^{k \times n}) \tag{6}$$

For $k = 1$, $P'_{n,k}$ is the probability of a successful complete transmission using scheme 4. It is clear that the probability obtained from (6) has been increased. By carefully choosing k and n, the time cost will be greatly reduced with not much more or even less energy consumption.

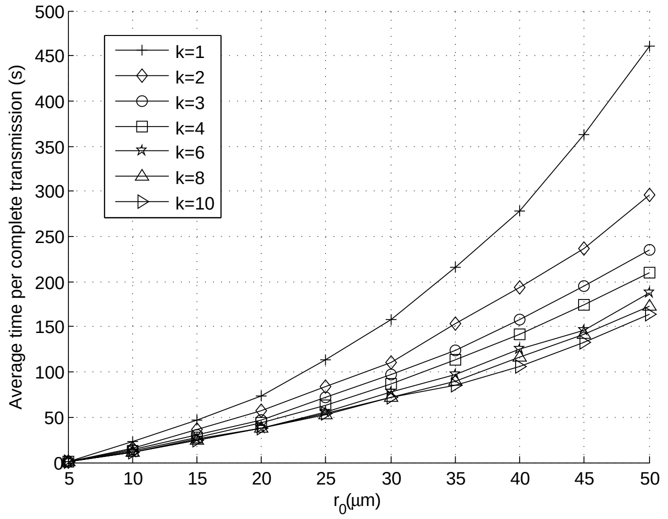

Figure 4: The time required for a complete transmission using scheme 2 under varying r_0 and with T_r = 8s (Note: k = 1 is also scheme 1).

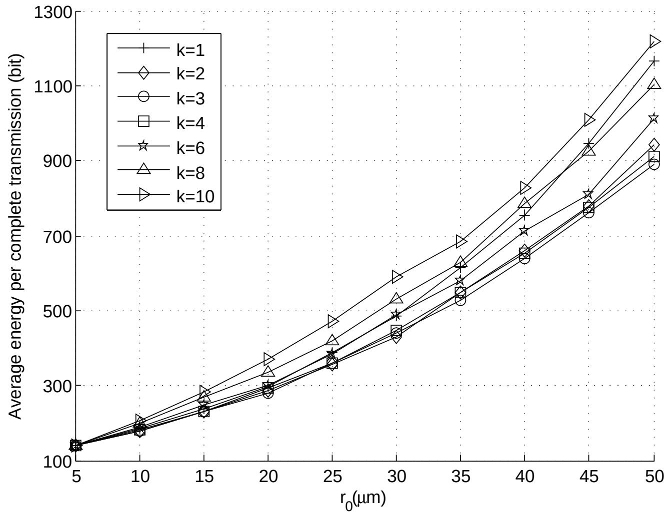

Figure 5: The energy required for a complete transmission using scheme 2 under varying r_0 and with T_r = 8s (Note: k = 1 is also scheme 1).

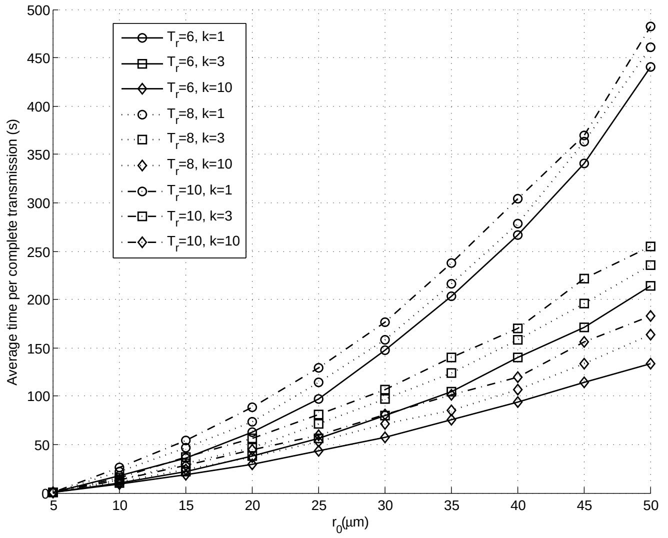

Figure 6: The time required for a complete transmission using scheme 2 under varying r_0 and k at T_r = 6s, 8s and 10s (Note: k = 1 is also scheme 1).

4. Simulation of the Schemes

The first figure of merit in evaluating these transmission schemes is energy consumption required for a complete transmission. Setting $m = 10$ and $i = 2$, the length of each packet and ACK is $l_P = 14$ and $l_A = 4$ (in bits), respectively. Thus the total amount of energy required for a successful complete transmission can be calculated by simply counting the overall bits transmitted by both Tx and Rx as:

$$\begin{aligned} \text{Energy} &= l_P \times N_P + l_A \times N_A \\ &= 14 \times N_P + 4 \times N_A \end{aligned} \tag{7}$$

where N_p is the number of packets required and N_a is the number of ACKs required assuming that each bit requires the same amount of energy. It can be noted that the unit of energy in this case is normalised to bits, thus allowing the reader to substitute their own energy model given by their own Tx-Rx nanomachines. The second figure of merit is the time for completion of a successful transmission under a given scheme and is calculated through simulation. It should also be noted that as this work being simulation-based, each of the subsequent results is the average of 15000 trials.

4.1. Schemes 1 and 2

The simulation results are based on schemes 1 and 2 with k varied from 1 to 10 ($k = 1$ is for scheme 1) and T_r = 8s. As is shown in Fig. 4, scheme 2 reduces significantly the time cost compared to scheme 1, and the results of both the schemes show the agreement with the relationship 'longer distance requires longer complete transmission time'. However, it should be also noticed that for a given r_0, the gain difference between k and $(k-1)$ decreases with an increasing value of k, which suggests that there may be an optimum value under this scheme.

It can be seen in Fig. 5 that with a fixed k, more energy is required to perform a complete transmission at longer distance, namely larger r_0, due to the rapid decrease of the capture probability. But what is not so intuitive is that with k getting larger, the probability of a successful transmission increases due to the lowering number of retransmission packets. With r_0 fixed, increasing k leads to higher probability of successful transmission based on the equation (3),but on the other hand, results in more energy consumption for the transmission of the ACKs. So if k is too large, the energy consumption for transmitting the

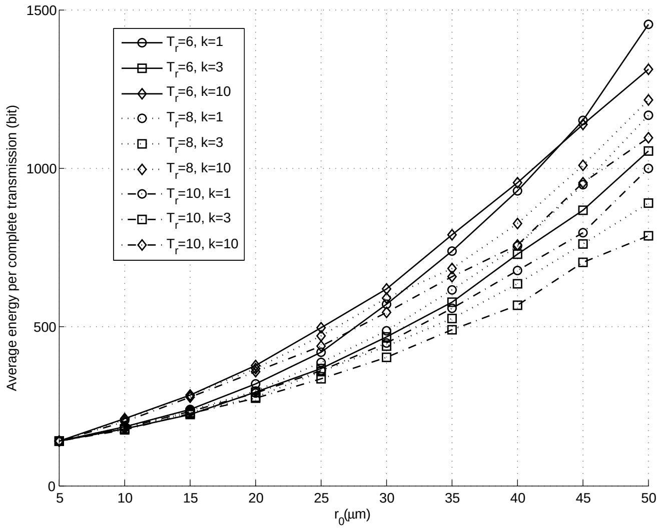

Figure 7: The energy required for a complete transmission using scheme 2 under varying r_0 and k at $T_r = 6\text{s}, 8\text{s}$ and 10s (Note: $k = 1$ is also scheme 1).

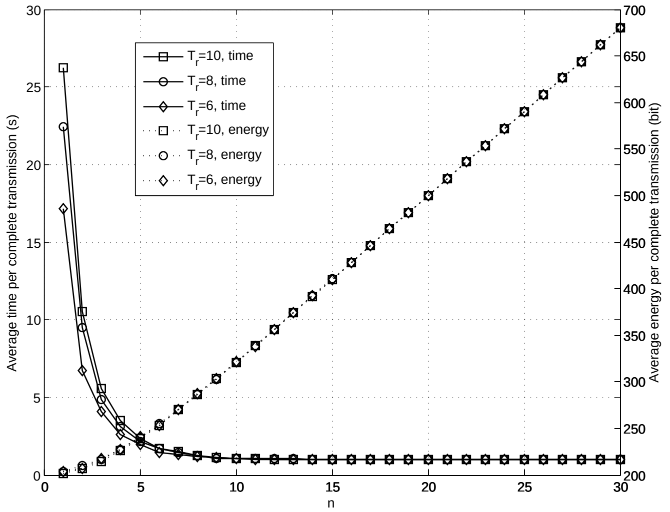

Figure 8: Scheme 3 time and energy trade-off for varying T_r and n at $r_0 = 10\mu$m (Note: $n = 1$ is scheme 1).

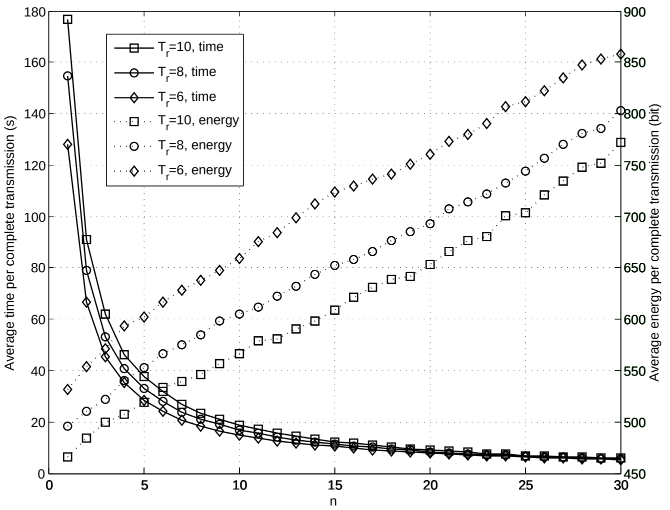

Figure 9: Scheme 3 time and energy trade-off for varying T_r and n at $r_0 = 30\mu$m (Note: $n = 1$ is scheme 1).

excess ACKs may outweigh the energy gain in requiring a lower number of transmission packets, which leads to an interesting trade-off as is shown in Fig. 5. Here, it is shown that the energy cost is actually lowest when $k = 3$ for the parameters used in this work.

Referring to Figs. 6 and 7, another variable, T_r, is varied to confirm that as T_r gets smaller (as the repeat-time is shorter), the time for complete transmission decreases with more energy required (as more re-transmissions are made). It is interesting that there may be a benefit in both time and energy to using a longer T_r with a larger k. For example, with $r_0 = 50\mu$m, for $T_r = 6$s and $k = 3$, the energy consumption is 1055 bits and the time cost is about 215s; for $T_r = 8$s and $k = 3$, the energy consumption is 891 bits, and the time cost is about 236s; and for $T_r = 10$s and $k = 3$, the energy consumption is about 786 bits, and the time cost is about 255s. That is, with T_r increasing from 6s to 8s and 10s, the energy consumption reduces 15% (for 8s) and 26% (for 10s), and the time cost increases 10% (for 8s) and 18% (for 10s). Depending on the scenario and system requirements, these parameters, namely k, r_0, and T_r, are available for the system designer to further refine.

4.2. Scheme 3

Aiming to minimize the transmission time without a disproportionate energy cost, scheme 3 introduces a new variable n, which represents the number of packets or ACKs sent at a single transmission. Figs. 8 through 10 show the time-energy trade-off over varying n, T_r, and r_0. For short distance communications, $r_0 = 10\mu$m, the capture probabilities as given by (1) are quite similar for $T_r = 6$s, $T_r = 8$s, and $T_r = 10$s. Thus, as can be seen in Fig. 8, there must exist a certain value of n for either value of T_r that minimizes the transmission time at the cost of only a little more energy consumption. It is also shown how superior this scheme is to scheme 1 ($n = 1$). When n increases from 1 to 5, at $T_r = 6$s, the time cost reduces from 17s to 2s (an 88% decrease), with only an energy consumption increase from 204bis to 241 bits (an 18% increase).

For medium distance communications, $r_0 = 30\mu$m, the capture probabilities for $T_r = 6$s, 8s and 10s are $0.0697, 0.0805$ and 0.0884 respectively. The difference leads to the different energy requirements, which can be seen in Fig. 9 that a system using $T_r = 6$s will always cost more energy than $T_r = 8$s and $T_r = 10$s. Another feature shown in the graph is that a trade-off does exist in this case by selecting the value of n, but it is also worthy to note another way of thinking here. For example, if a system is designed with an average transmission time of 10s, the possible options are a system with $T_r = 10$s and $n = 18$,

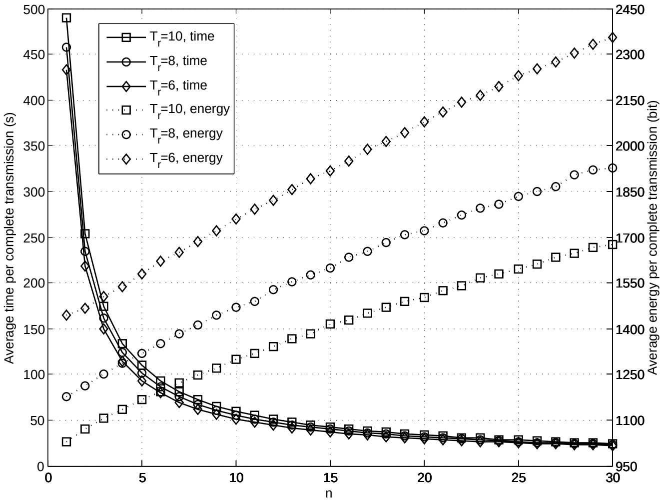

Figure 10: Scheme 3 time and energy trade-off for varying T_r and n at $r_0 = 50\mu$m (Note: $n = 1$ is scheme 1).

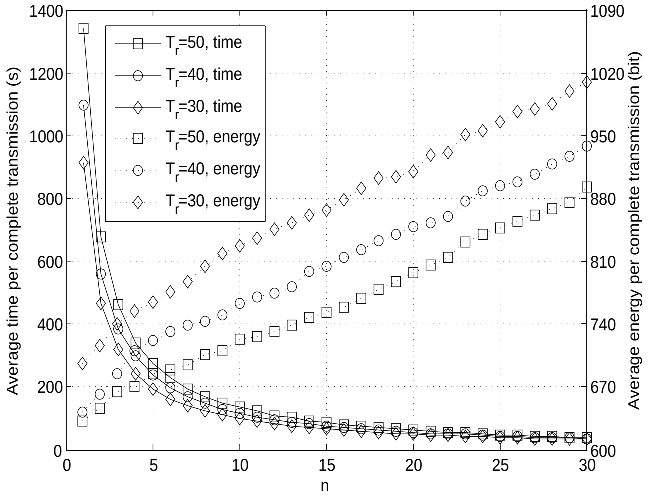

Figure 11: Scheme 3 time and energy for varying lengthier T_r and n at $r_0 = 50\mu$m (Note: $n = 1$ is scheme 1).

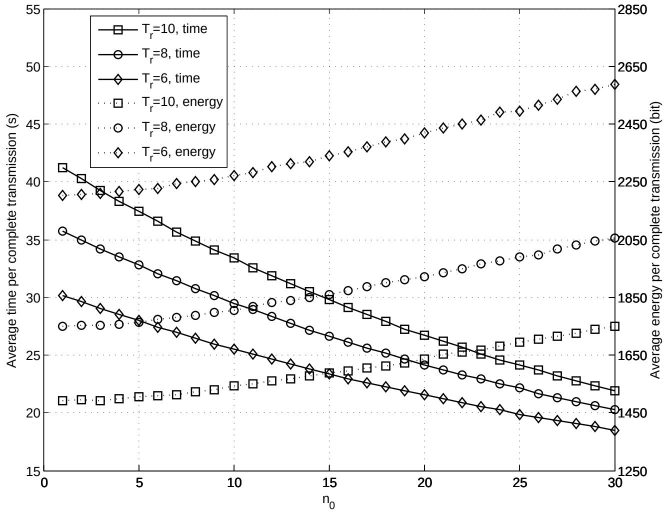

Figure 12: Scheme 4 time and energy trade-off for varying T_r and n_0 at $r_0 = 50\mu$m.

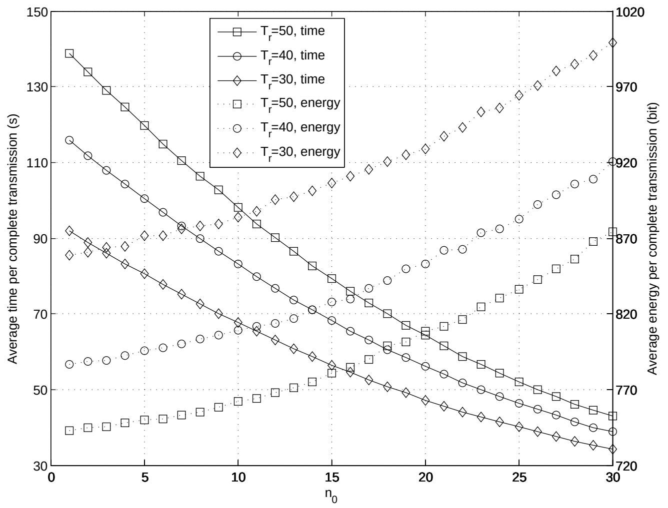

Figure 13: Further scheme 4 time and energy trade-off for varying T_r and n_0 at $r_0 = 50\mu$m.

or $T_r = 8$s and $n = 17$, or $T_r = 6$s and $n = 16$. Obviously, the first option is the best one as the least energy is required.

At long transmission distances, $r_0 = 50\mu$m, the difference of the capture probability given by (1) is at such an extreme for the short value of T_r considered. As is shown in Fig. 10, although the energy requirements are in agreement with the above, they are disproportionally high and possibly not feasible within the limited energy envelope nanomachines can utilize or provide. However, slowing down the system by setting the repeat-time as $T_r = 30$s, $T_r = 40$s, and $T_r = 50$s may improve the performance. The capture probabilities for $T_r = 30$s, $T_r = 40$s, and $T_r = 50$s are 0.0514, 0.0572, and 0.0614 respectively. Similar to before, $T_r = 50$s always uses the least amount of energy. Furthermore, by comparing the results shown in Fig. 10 and Fig. 11, if an average transmission time of 39s is required, for $T_r = 10$s, it needs 1435 bits of energy whilst for $T_r = 50$s, only 893 bits of energy can be enough to support the complete transmission.

4.3. Scheme 4

Scheme 4 is designed to obtain an 'adaptive' transmission scheme, especially for long range communications. Unlike scheme 3 being fixed, the number of packets and ACKs sent in a single transmission is alterable depending on the success or failure of previous transmission. The initial number, n_0, is also varied from 1 to 30 (for scheme 3, n is always equal to n_0).

By comparing the results shown in Figs. 10 and 12, the performance has been improved significantly using scheme 4 instead of scheme 3 when n_0 is small, but when n_0 gets larger, the performance is similar. For example, with $T_r =$

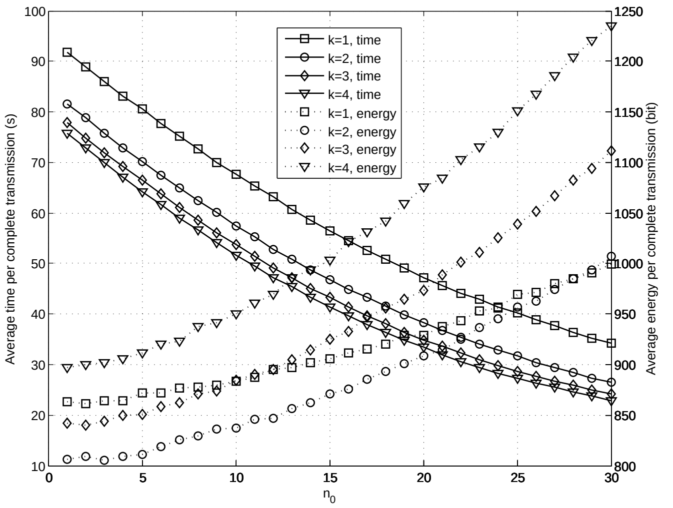

Figure 14: Scheme 5 time and energy trade-off for varying n_0 and k at $T_r = 30$s and $r_0 = 50\mu$m (Note: $k = 1$ is also scheme 4).

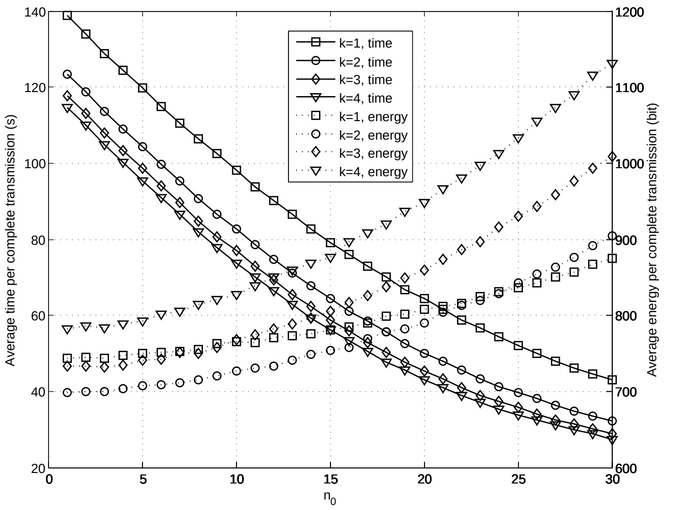

Figure 15: Scheme 5 time and energy trade-off for varying n_0 and k at $T_r = 50$s and $r_0 = 50\mu$m (Note: $k = 1$ is also scheme 4).

10s and $n_0 = 1$, using scheme 3, time cost is 490s, and the energy consumption is 1030 bits, whilst using scheme 4 the time cost is 41s (a 92% decrease) and the energy consumption is 1493 bits (a 45% increase). If the time cost is limited to 25s, the energy consumption based on scheme 3 is 1667 bits, and the energy consumption based on scheme 4 is 1669 bits. Similar results could be found with $T_r = 30$s, 40s, and 50s (shown in Fig. 13).

4.4. Scheme 5

Using scheme 5 will greatly increase the probability of a successful complete transmission by increasing the probability of the successful ACK transmission, especially for long distance communications. As is shown in Fig. 14 and Fig. 15, by introducing a new variable k, the time cost for a complete transmission has been reduced significantly due to the increase of the probability of a successful transmission given by (6). However, the increase of such probability will not lead to the decrease of the energy consumption because the energy cost for sending excess ACKs also contribute to the overall energy consumption. When n_0 is quite large, the energy gain of having more ACKs may outweigh the energy gain in requiring a lower number of transmission packets especially if l, given by (4), is small. For example, as shown in Fig. 14, when n_0 is small, energy consumption for $k = 1$ is significantly higher than that for $k = 2$ and $k = 3$, but with the increasing n_0, energy consumption for $k = 1$ is lower than that for $k = 3$ (after $n_0 = 11$) and $k = 2$ (after $n_0 = 28$). Similar results are shown in Fig. 15 for simulations with $T_r = 50$s and $r_0 = 50\mu$m.

By comparing the results shown in Figs. 11, 13 and 15, with $T_r = 50$s and $r_0 = 50\mu$m, if time cost is limited to 75s, the energy consumption based on schemes 3, 4 and 5($k = 2$) can be obtained as 777 bits, 777 bits and 733 bits which clearly shows the at longer distances scheme 5 clearly has better energy performance when k is carefully chosen.

5. Conclusions

In this paper, simulation results are provided on five SW-ARQ schemes with the diffusion-based molecular communication system. The performance is analyzed with regards to the time cost (average time per successful complete transmission) and the energy consumption (average energy per successful complete transmission). It is shown that all five schemes could be used as communication protocols between two nanomachines. To be specific, for adjacent communications scheme 1 is the first choice for its own simplicity, while for longer range communications schemes 2 and 3 (especially scheme 3), will improve the performance significantly with sufficient energy. Unlike schemes 1 through 3 which target applications with the pre-known channel, schemes 4 and 5 are designed for a unknown channel or a varying channel due to the algorithm adaptivity. Similar to the comparisons between scheme 2 and scheme 1, scheme 5 will provide better performance than scheme 4 with carefully designed parameters and sufficient energy. Besides, when designing a communication system, the complexity of the system should also be taken into consideration. In the future for specific systems with limitation on time cost or energy consumption, optimizations of the trade-off between the time and energy requirement will be of great importance.

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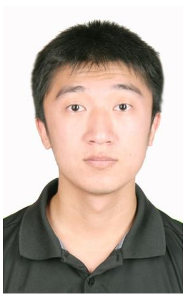

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