An Autonomous Selective Cooperative ARQ Protocol for Hybrid Mobile Wireless Sensor Networks

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***Abstract*— This paper presents a new cooperative ARQ protocol for a hybrid mobile wireless sensor network. The mobile relay nodes decode the signal from the source sensor using cyclic redundancy check (CRC) and forward it to the destination sink. A distributed relay selection that exploits overhearing of inter-relay node transmission is employed to achieve higher selection diversity gain during retransmissions. Upon reception from the source sensor, the number of relay nodes available to contend for transmission depends on the conditions of source-relay channels. When source-relay channels are instantaneously poor, achievable selection diversity gain decreases. Such relay availability dependency over source-relay channels can be reduced if erroneous relays exploit inter-relay channels to opportunistically listen (*OL*) to the transmission of the error-free selected relay. By combining the initially received erroneous signals with the signal overheard from the selected relay and decoding again, erroneous relays may be able to decode the signals successfully thanks to the spatial diversity. This results in an increase in relay availability for distributed selection in subsequent retransmissions. It is also shown that the selection protocol based on end to end channel quality approach cannot make full use of the increased relay availability. The proposed cooperative ARQ protocol ensures to make full use of the increased relay availability. The numerical results show that the proposed cooperative ARQ significantly improves the successful packet arrival rate.**

***Index Terms*— cooperative ARQ; hybrid wireless mobile sensor network; distributed relay selection; opportunistic listening; cooperative diversity; multihop relay**

I. INTRODUCTION

As a solution for conserving power, enhancing coverage and connectivity in large scale sensing networks, an idea to integrate sensors and mobile enabled radio communication devices has been laid out to realize hybrid cellular-sensor networks. There are three main tiers in the architecture of such hybrid systems: sensor tier, mobile (relay) tier and base station (destination) tier [1]. Mobile phones and radio enabled context aware devices can spare more resources in power and computational capability, and they can transmit longer range than sensors. Such mobile terminals may be used as a bridge to connect isolated and clustered sensors to base station. Fig. 1 illustrates the concept of a generic hybrid mobile wireless sensor network. In that concept, mobile terminals nearby collect information accumulated in sensor tier and serve as carriers in relaying the information to the base station (destination) [1][2][3].

A number of researches have been carried out for hybrid mobile wireless sensor networks in issues related to searching potential relay nodes, packet delivery delay and protocols to exploit mobility [1][2][4]. This paper focuses on reliable and efficient delivery of packets in physical layer mainly in mobile relay tier and the destination. In wireless mobile sensor networks, network topology is dynamical due to relative mobility among the associated nodes. Thus, channel along the path from source sensor to destination is variant, requiring mitigation of fading channel. This paper proposes a new cooperative ARQ protocol that overcomes the limitation of source-relay channel on the achievable cooperative diversity gain by employing a distributed relay selection that exploits overhearing from inter-relay nodes channels.

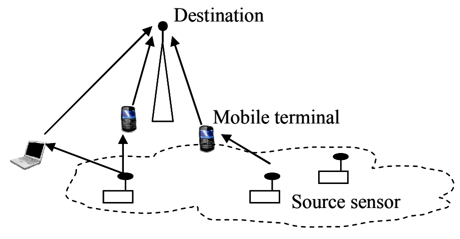

Figure 1 Wide area hybrid mobile wireless sensor network

When there are multiple relay nodes to collect data from the sensor tier in the hybrid network depicted in Fig.1, spatial diversity gain can be realized by the relays at different locations transmitting the same information to destination node in a cooperative manner [5]. Such diversity gain derived from the cooperation of relay

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nodes is known as cooperative diversity. The simplest way to achieve diversity is repetition-based cooperation in which each relay node transmits in its orthogonal sub-channel, in time or frequency, at the price of poor bandwidth efficiency [6][7]. [7][8] proposes distributed space-time code (STC) transmission that does not require orthogonal sub-channels. On the other hand, the distributed STC needs to have symbol level synchronization to coherently combine transmitted signals from the cooperating relays. This is very challenging if cooperating relay nodes are mobile. Moreover, traditional orthogonal STC was designed for a fixed number of antennas and it has no rate-one code to support more than two antennas. Thus, distributed STC based relay cooperation can not guarantee full rate full diversity for an arbitrary number of relay nodes.

For realizing a reliable communication, automatic repeat request (ARQ) is indispensible. In multihop networks, relay nodes not only forward information but also serve as re-transmitters. Such ARQ operation carried out by relay nodes is called cooperative ARQ.

Meanwhile, relay selection [9][10][11] has been considered as a simpler alternative to STC because of its ability to achieve the same diversity order while actual transmission involves single node. Thus, selection based cooperation efficiently utilizes resources of cooperating relays while providing diversity gain, which is desirable from the aspect of conserving energy. In [9][10], selection based cooperative ARQ is presented; however, they did not consider selection protocols that enable relay nodes to cooperate in a distributed manner. In [11], a transmit time-offset based distributed relay selection technique is presented. In that technique, none of the nodes takes the leading role to decide the best relay, instead each relay node assigns itself a transmit time-offset (a timer) which is inversely proportional to the instantaneous channel quality. During a contention period, each relay node counts down the timer till it reaches zero, at which point relay transmission initiates. Each cooperating relay is in receive-mode or carrier sense mode to detect other relay's transmission while timer is counted down. Obviously, the relay node with the best channel quality will have the smallest timer value and thus, it transmits first among all the relays. As it transmits, the other relays hear the transmission and stop their competition to transmit. As a result, selection is realized in a distributed manner.

In selection based cooperation, the actual number of relay nodes available for selection depends on the channels between source sensor to relay nodes (hereafter source-relay channels). Due to instantaneous deep fading in the source-relay channels, some relay nodes may not successfully receive the signal transmitted by the source. This decreases the achievable selection diversity gain. It should be noted that even though a relay may have poor instantaneous incoming channel, its outgoing transmit channel may be good because the channel on one side is independent from that on the other side. If we can make use of such relay in forwarding the signal, improved performance can be expected.

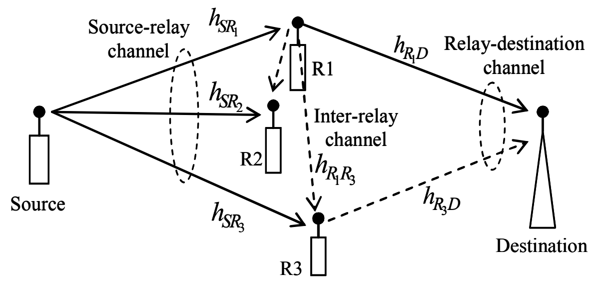

Figure 2 System model.

In this paper, we consider a two-hop hybrid wireless mobile sensor network with *N* mobile terminals serving as relay nodes as shown in Fig. 2. The source sensor is located beyond the coverage of the destination. Upon receiving the signal from the source, the relays whose cyclic redundancy check (CRC) results show correct reception contend for transmission to further forward the signal to the destination. Transmission to the destination is carried out by the best relay decided by a distributed relay selection technique similar to that of [11]. As the best relay transmits, the erroneous relays capture the signal and combine it with their erroneous signals and decode the combined signal; we refer to this as inter-relay opportunistic listening (*OL*). Thanks to the spatial diversity established by *OL*, the erroneous relays may become error-free and available to be selected for subsequent retransmission, if requested. This yields higher selection diversity order for retransmission. Suppose information on relay-destination channel (h_{RD}) quality is available at each relay, decentralized nature of distributed selection allows each relay to independently decide whether to contend for transmission or not based on its cyclic redundancy check (CRC) result. Thus, the proposed cooperative ARQ protocol provides autonomy to relays. In addition, we show that conventional approach of using the end-to-end channel quality measure in distributed relay selection cannot efficiently utilize increased selection diversity gain offered by proposed cooperative ARQ. Our protocol uses relay-destination channel only to make full use of increased diversity gain in retransmission. Performance of the proposed cooperative ARQ protocol is verified in terms of packet error rate (PER) and packet arrival rate (PAR) by simulations as well as theoretical analysis.

Section II details system assumptions and our cooperative ARQ protocol. A theoretical error rate performance analysis of the system is provided in Section III. Simulation assumptions and parameters are presented in Section IV. Numerical results are presented in Section V. Finally Section VI concludes the paper.

II. System Descriptions

Suppose source sensor in Fig.2 has accumulated information to be transmitted. The potential relay nodes, which are mobile terminals, are located at the distances where both the source and the destination can communicate to. Traditionally, a group of relay nodes with maximum instantaneous harmonic mean function of source-relay and relay-destination channel gains [12] are decided as relay nodes. For the system under consideration, the decision to serve as relay nodes should be made by the potential relay nodes themselves employing an SNR threshold in source-relay channels. It is assumed that the relay nodes are synchronized in time-slot level. Since the relay nodes are connected to single destination node, synchronization among the relay nodes can be easily realized by means of common timing signal from the destination.

After forming the cooperation group with N relay nodes, source and relay transmissions are carried out in orthogonal time slots as explained in the following referring to the Fig. 3. Firstly, suppose the source broadcasts the n^{th} information packet to the relay nodes in the 1st slot. The relay nodes employ decode and forward (DF) to avoid noise amplification and error propagation associated with amplify and forward (AF). The relay nodes check if their received signals have errors using CRC. In the beginning of the 2nd slot, the relay nodes which receive the signal correctly contend for the transmission by means of distributed relay selection. The distributed relay selection used in this paper is similar to that in [11] in that it uses transmit time-offset, however, different in channel quality decision rule. Assuming each relay node R_i, $i \in \{1,...,N\}$, has knowledge on its channel quality a_i, the transmit time-offset is calculated as $\tau_i = \frac{\lambda}{a_i}$, where λ is a constant having unit of time since a_i is a scalar. The best relay node is the one which has $\max\{a_i\}$, i.e. $\min\{\tau_i\}$. The parameter λ incurs a trade-off between the speed of distributed selection process and relay transmission collision. It is referred to [11] for the analysis of collision probability as a function of λ. Assuming only one packet of information is transmitted in a slot, the duration of time slot T_{slot} assigned for relay transmission is larger than the data packet duration T_{pkt} to provide contention time in the distributed relay selection. The maximum allowable time-offset ($\tau_{\max}$) should then be $\tau_{\max} \le T_{\text{slot}} - T_{\text{pkt}}$. If none of the relays correctly receive the signal from the source, they stay idle without transmitting in the 2nd slot. If none of the relays transmits until the time elapsed from the beginning of the 2nd slot exceeds $\tau_{\max}$, the source retransmits the same packet. Thus, ACK and NACK are not necessary in the source-relay channel. This is plausible for the autonomous source sensor that no decoding for ACK/NACK is necessary. Also, a coarse synchronization of the source with the relay nodes is possible since $\tau_{\max}$ is predetermined.

Suppose that N_1, $N_1 \le N$, relay nodes correctly receive the signal from the source. Without loss of generality, these N_1 relays are indexed starting from one as $i \in \{1,...,N_1\}$. They compete for transmission by counting down their transmit time-offsets starting from the beginning of the 2nd time slot. The index of the best relay node for the initial relay transmission is

$$k = \arg\max_i \{a_i\} \Leftrightarrow \tau_k = \min\{\tau_i\}, i \in \{1,...,N_1\} . \quad (1)$$

As relay node R_k transmits, N–N_1 erroneous relay nodes opportunistically listen to the transmission and combine the transmit packet of R_k with their erroneous packets and decode again. Chase combining (CC) [13] is employed in combining the packets. Thanks to the spatial diversity offered by *OL*, some of the N–N_1 erroneous relay nodes may successfully decode their Chase-combined packets. This may increase the number of relay nodes whose CRC results show correct reception to N_2, where $N_1 \le N_2 \le N$, at the end of the 2nd slot. If the destination successfully receives R_k's transmission, relaying for n^{th} packet is completed in the 2nd slot. It is assumed that an ARQ feedback channel follows the data transmission channel as shown in Fig. 3. If the destination fails to correctly receive the initial relay transmission, retransmission from the relay nodes is requested. For retransmission in the 3rd slot, N_2 relay nodes are available to compete for retransmission. As we see, relay availability for retransmission is increased thanks to *OL*. If a simple distributed selection scheme without *OL* is used, the selection diversity order will be the same (N_1) in both the initial transmission and retransmission.

A. Effect of Channel Quality Decision Rules

Conventionally, the relay selection scheme as in [11] determines the end-to-end channel quality of relay R_i from the source-relay h_{SR_i} and relay-destination h_{R_iD} channels as

$$a_i = \min\{|h_{SR_i}|^2, |h_{R_iD}|^2\} . \quad (2)$$

Given the a_i of each relay node from (2), the best relay node for initial relay transmission is given by (1). The drawback of channel quality decision rule of (2) in our cooperative ARQ is explained using Fig. 3. Fig. 3 includes a snapshot example showing instantaneous channel rank of each relay node and their CRC results, *OK* or *NG*. As seen in Fig. 3, R_3 has the poorest source-relay channel and its received signal from the source has errors (CRC: *NG*) while its relay-destination channel is the best, where $|h_{SR_3}| < |h_{R_3D}|$. R_1 and R_2 successfully receive the signal from the source (CRC: *OK*s) and they compete for transmission in the 2nd slot. If $a_2 > a_1$, R_2 will transmit first since $\tau_2 < \tau_1$ according to (1). As R_2 transmits, R_1 stops its attempt to transmit whereas R_3 listens to R_2's transmission to combine the packet with its erroneous received packet and decode the combined packet. At this time, R_3 successfully decodes its signal (CRC: *NG*→*OK*) thanks to the spatial diversity created by exploiting R_2's transmission. Now R_3 becomes ready to participate in distributed selection in the 3rd slot if retransmission is requested by the destination. However, if $\min\{|h_{SR_3}|^2, |h_{R_3D}|^2\}$ is taken as end-to-end channel quality according to the conventional selection protocol, τ_3 will be the largest. As a result, R_3 will have no chance to transmit even though it has the best relay-destination channel condition. This clearly shows that end-to-end

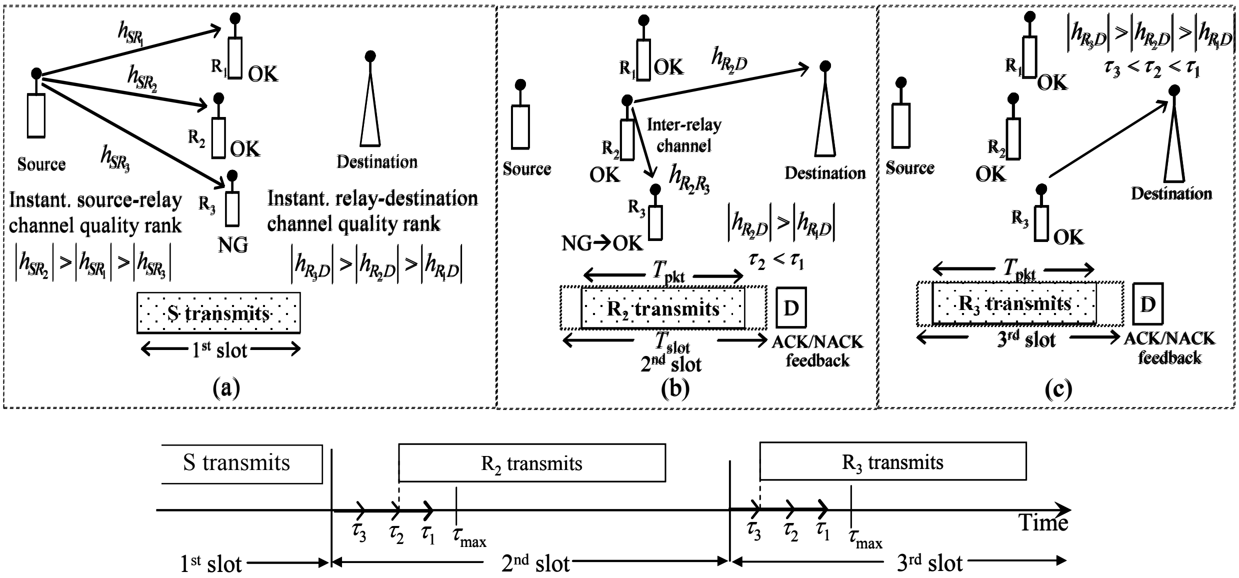

Figure 3 Operational procedure of the proposed cooperative ARQ protocol and access timeline: (a) *S* transmits; (b) *R* transmits; (c) *R* retransmits

channel quality rule cannot take full advantage of increased relay availability in our cooperative ARQ.

In our system, as a result of exploiting inter-relay channels, relay availability dependency over the source-relay channels decreases in subsequent retransmission. Thus, in our distributed selection, the channel quality of each relay is determined based on the relay-destination channel only in computing the transmit time-offsets. In the proposed protocol, for transmission in the 2nd slot, each relay R_i, $i\in\{1,...,N_1\}$, determines its channel quality as

$$a_i = \left|h_{R_i D}\right|^2, i \in \{1,...,N_1\}. \tag{3}$$

With a_i from (3), R_i determines τ_i and the index of the best relay node is given by (1). After listening to the transmission of the best relay (R_k), the number of relay nodes whose CRC results show correct reception becomes N_2. Again, without loss of generality, N_2–N_1 newly available relays are indexed starting from N_1+1 as $\{N_1+1,...,N_2\}$. In a slowly varying channel environment, the channel conditions in initial transmission and in retransmission slots may be almost the same. Hence, the channel rank of the relays may also be the same. Thus, only R_k and the N_2–N_1 newly available relay nodes need to compete in the distributed relay selection when retransmission is requested. For retransmission, each relay R_j, $j\in\{k,N_1+1,...,N_2\}$, determines its channel quality as in (3). The index of the best relay for retransmission is

$$l = \arg\max_j \{a_j\} \Leftrightarrow \tau_l = \min\{\tau_j\}, j \in \{k, N_1+1,...,N_2\}. \tag{4}$$

From the example in Fig. 3, R_3 becomes error-free thanks to *OL* and competes with R_2, which is the best relay in initial transmission, for transmission in the 3rd slot. Since R_3 has a better relay-destination channel than R_2, R_3 will transmit in the 3rd slot according to (4). By Chase-combining of the initial packet from R_2 and the retransmitted packet from R_3, the destination achieves additional diversity gain which is not available with conventional distributed selection. To provide

<u>Proposed cooperative ARQ protocol</u>

S transmits in the <u>1st slot</u>

Each R_i, $i\in\{1,...,N\}$ check CRC
- Case 1 All *N* relays CRC: *OK*
- Case 2 All *N* relays CRC: *NG*
- Case 3 N_1, $1\le N_1<N$, relays CRC: *OK*

Each R_i, $i\in\{1,...,N\}$ decides τ_i using (3) and $\tau_i = \frac{\lambda}{a_i}$

If **Case 1**

R_k, *k* given by (1) out of *N* relays transmits at τ_k in the <u>2nd slot</u>
  - *If* (CRC at *D*: *NG*)
    - Retransmission by R_k in the <u>3rd slot</u>
  - *End*

If **Case 2**

S retransmits after τ_{max} in the <u>2nd slot</u>
  - *If* (N_m, $N_m\le N$, relays CRC: *OK*)
    - R_k, *k* given by (1) out of N_m relays transmits at τ_k in the <u>3rd slot</u>
  - *Else if* (only R_j's CRC: *OK*)
    - R_j transmits in the <u>3rd slot</u>
  - *End*

If **Case 3**

R_k, *k* given by (1) out of N_1 relays transmits at τ_k in the <u>2nd slot</u>
  - *OL* by erroneous relay R_f, $f\in\{N_1+1,...,N\}$
  - *If* (CRC at *D*: *NG*)
    - R_l, *l* given by (4) out of N_2–N_1+1 relays transmits at τ_k in the <u>3rd slot</u>
  - *End*

h_{R_iD} information to each relay node to decide τ_i, the destination may broadcast a common pilot at a regular interval well before the channels change; channel reciprocity in time-division-duplex (TDD) allows relays to estimate h_{R_iD} using the pilot [14]. The flow of proposed cooperative ARQ protocol is described, assuming number of maximum retransmission being one and denoting source and destination as S and D respectively.

III. Error Rate Analysis

In this section, the error-rate analysis of the system under consideration is presented on case by case basis. For the sake of simplicity, the theoretical analysis assumes BPSK data modulation. However, the simulation results with QPSK and QAM data modulations will also be provided in Section V. Number of retransmissions either by the source or relay is limited to one.

We denote the source-relay channels, relay-destination channels and inter-relay channels as h_{SR_i} , h_{R_iD} and $h_{R_iR_j}$; the corresponding instantaneous SNRs as $\gamma_{uv} = |h_{uv}|^2 \cdot (\frac{E_S}{N_0})$; the averaged SNRs as $\overline{\gamma}_{uv} = E[|h_{uv}|^2] \cdot (\frac{E_S}{N_0})$, respectively with $u \in \{S, R_i\}$, $v \in \{R_i, D\}$, $i=\{1,\ldots,N\}$ and $E[.]$ denote the ensemble average. E_S/N_0 is the signal energy per bit-to-additive white Gaussian noise (AWGN) spectrum density ratio (SNR). Each node in our system are assumed to have single omnidirectional antenna and each channel is subject to independent flat fading. In addition, the channels do not change during initial transmission and retransmission times.

A. Element Error Rates

Upon receiving the signal from the source in the 1st slot, the possible relay errors can be classified into three cases.

Case 1) All relays correctly receive the signal.

Case 2) None of the relays correctly receive the signal.

Case 3) Some of the relays correctly receive the signal while some do not.

The achievable performance in the relay-destination channel depends on the relay error case. In the following, before deriving the expressions for end-to-end error performance in each case, we first give the expressions for basic error rates.

1) Error Probability at Each Relay Node

After receiving from the source in the 1st slot, the average bit error rate (BER) at each R_i, assuming BPSK modulation in a flat Rayleigh fading channel, is given by [15]

$$P_{b,1}\left(\overline{\gamma}_{SR_i}\right) = \int_0^\infty \frac{1}{2} erfc\left(\sqrt{\gamma_{SR_i}}\right) f_{\gamma_{SR_i}}\left(\gamma_{SR_i}\right) d\gamma_{SR_i} \tag{5}$$

where $f_\gamma(\gamma)$ denotes the chi-square distributed probability density function (PDF) of received SNR and $erfc(.)$ is the complementary error function. Assuming channel is static throughout a packet that consists of N_b bits, the PER at each relay node can be expressed as

$$P_{p,1}(\overline{\gamma}_{SR_i}) = 1 - (1 - P_{b,1}(\overline{\gamma}_{SR_i}))^{N_b} \tag{6}$$

2) N-branch Selection Diversity

If all N relay nodes successfully receive the signal from the source, the selected relay node transmits to the destination, achieving N-branch selection diversity. Given N relay nodes are available in relay selection, the average PER of N-branch selection diversity in Rayleigh fading can be expressed as [16]

$$P_{p,\text{SEL}} = \sum_{i=1}^{N} \int_0^\infty (1-(1-P_{b,1}(\gamma_{R_iD}))^{N_b} f_{\gamma_{R_iD}}\left(\gamma_{R_iD}\right) \prod_{j=1, j\neq i}^{N} F_{\gamma_{R_jD}}(\gamma_{R_iD}) d\gamma_{R_iD} . \tag{7}$$

From (7), $F_{\gamma_{R_jD}}\left(\gamma_{R_iD}\right)$ is the probability that j^{th} relay's relay-destination channel SNR is lower than that of i^{th} relay and can be expressed as

$$F_{\gamma_{R_jD}}\left(\gamma_{R_iD}\right) = \int_0^{\gamma_{R_iD}} f_{\gamma_{R_jD}}(\gamma_{R_jD}) d\gamma_{R_jD} = 1 - \exp\left(-\gamma_{R_iD} \big/ \overline{\gamma}_{R_jD}\right), \tag{8}$$

where, $f_\gamma(\gamma) = \frac{1}{\overline{\gamma}} \exp(\frac{-\gamma}{\overline{\gamma}})$.

3) Error Probability with ARQ at Each Relay

When none of the relay nodes successfully receives the signal, the source sensor retransmits the same signal in the 2nd slot. In this case, the error probability with ARQ at each relay is the error probability at retransmission conditioned on that of initial transmission. With BPSK data modulation, the probability that a bit error occurs during initial transmission time is given by

$$\Pr_e\left(h_{SR_i}\right) = erfc\left(\left|\text{Re}(h_{SR_i})\right| \Big/ \sqrt{2\sigma^2}\right), \tag{9}$$

where $2\sigma^2$ is the variance of the noise. In terms of packet, the error probability in the initial transmission can be expressed as,

$$\Pr_p(h_{SR_i}) = 1 - \left(1 - \Pr_e(h_{SR_i})\right)^{N_b} . \tag{10}$$

Assuming a slow channel, the channel is invariant during retransmission time, resulting in the SNR of the Chase-combined received signal to be twice as that of the initial received signal. Then, the average PER with ARQ at each relay node is the packet error probability with $\text{SNR} = 2\gamma_{\text{SR}_\text{i}}$ at the retransmission time conditioned on $\Pr_p(h_{SR_i})$ as,

$$P_{p,\text{ARQ}_{SR_i}} = \int_0^\infty \left(1 - \left\{1 - \left(\Pr_p(h_{SR_i})\right) P_{b,1}(2\gamma_{SR_i})\right\}^{N_b}\right) f_{\gamma_{SR_i}}\left(\gamma_{SR_i}\right) d\gamma_{SR_i} . \tag{11}$$

Similarly, if the same relay transmits to the destination at both initial transmission and retransmission, the PER at the destination, denoted as $P_{p,\text{ARQ}_{R_iD}}$, is also given by (11) by substituting the corresponding h_{R_iD} and γ_{R_iD} .

4) Error Probability with Selection and ARQ

If all N relays successfully receive the signal from the source sensor, the selected relay transmits to the destination in the 2nd slot. When the destination fails to receive the initial transmission correctly, the same relay retransmits since the channel quality rank of the relays does not change. Thus, in addition to the selection diversity, 3dB SNR improvement is achieved at retransmission time. Following the N-branch selection diversity in (7) and ARQ in (11), the average PER at the destination can be deduced as

$$P_{p,\text{SEL-ARQ}} = \sum_{i=1}^{N} \int_0^\infty \left(1 - \left\{ 1 - \left(\Pr_p(h_{R_iD}) \right) P_{b,1}(2\gamma_{R_iD}) \right\}^{N_b} \right) f_{\gamma_{R_iD}}(\gamma_{R_iD}) \prod_{j=1, j\neq i}^{N} F_{\gamma_{R_jD}}(\gamma_{R_iD}) d\gamma_{R_iD} . \quad (12)$$

5) ARQ by Different Relays (2-branch Diversity)

Recall that in our cooperative ARQ, thanks to *OL*, achievable selection diversity increases in sub-sequent retransmissions. Thus, the relay node selected for retransmission may be different from that transmitted in initial transmission. When the different relay node is selected, two-branch diversity is achieved at the destination with effective SNR, $\gamma_{R_iD,R_jD} = \gamma_{R_iD} + \gamma_{R_jD}$ [17], where $i \neq j$. Similarly, the effective SNR after *OL* at an initially erroneous R_l is $\gamma_{OL,R_l} = \gamma_{SR_l} + \gamma_{R_lR_k}$, where R_k is the selected relay whose transmission is listened by R_l in the 2[nd] slot. The average PER with 2-branch diversity at the destination and that at the opportunistically listening relay are denoted as $P_{p,2}(\bar{\gamma}_{R_iD,R_jD})$ and $P_{p,2}(\bar{\gamma}_{OL,R_l})$ respectively.

B. End to End Packet Error Rate (PER)

Based on the element error rates, the error rate expressions for each case of the relay errors are derived in this subsection. For an arbitrary number of relay nodes, the numbers (N_1, N_2) and the set of relays available for selection is an indeterministic value. This means that probability calculations will have to be carried out for all possible combinations of relay nodes. Thus, for simplicity in theoretical presentations, N = 2 is used in the theoretical analysis.

1) Case 1(All N Relays' CRC: OKs)

The end-to-end packet error probability of this case is the PER given by selection and ARQ in (12) conditioned on the probability that all N relays correctly receive the signal from the source.

$$P_p^{c1} = \prod_{i=1}^{2} \left(1 - P_{p,1}(\bar{\gamma}_{SR_i}) \right) \times P_{p,\text{SEL-ARQ}} . \quad (13)$$

2) Case 2 (All N Relays' CRC: NGs)

When none of the relay nodes successfully receives the signal from the source, the source retransmits in the 2[nd] slot. The occurrence probability of case 2 is $\prod_{i=1}^{2} P_{p,1}(\bar{\gamma}_{SR_i})$. Upon receiving the retransmitted packet, there are three cases of relay errors.

i) Some relays become error-free: in this case, the relay node with the best h_{RD} transmits in the 3[rd] time slot. Note that, the selection diversity achieved in this case is conditioned on N_m, $N_m \leq N$, relays becoming error-free at the retransmission. With N = 2, N_m = 2. Hence, the conditional error probability in this case is

$$P_p^{c2.1} = \left(\prod_{i=1}^{N_m=2} \left(1 - P_{p,\text{ARQ}_{SR_i}} \right) \right) \cdot P_{p,\text{SEL}} . \quad (14)$$

ii) Only one relay becomes error-free: the error-free relay transmits in the 3[rd] time slot. The conditional error probability of this case is given by

$$P_p^{c2.2} = \sum_{i,j=1}^{2} \left\{ \left(1 - P_{p,\text{ARQ}_{SR_i}} \right) \cdot P_{p,\text{ARQ}_{SR_j}} \cdot P_{p,1}\left(\bar{\gamma}_{R_iD} \right) \right\} i, j = \{1,2\}, \forall i \neq j . \quad (15)$$

iii) All relays keep on having errors: the PER probability in this case is

$$P_p^{c2.3} = \prod_{i=1}^{N=2} P_{p,\text{ARQ}_{SR_i}} . \quad (16)$$

Since the occurrence probability of case 2 is the a priori probability for each sub-case, the total end to end PER of case 2 is

$$P_p^{c2} = \prod_{i=1}^{2} P_{p,1}(\bar{\gamma}_{SR_i}) \left\{ P_p^{c2.1} + P_p^{c2.2} + P_p^{c2.3} \right\} . \quad (17)$$

3) Case 3 (N_1 Relays' CRC: OKs)

In this case, there are N_1, $N_1 < N$, relay nodes that can participate in the distributed relay selection in the 2[nd] slot. Opportunistic listening (*OL*) is carried out in this particular case. Among N_1 relay nodes that have correctly received the signal from the source, the relay node with the best relay-destination channel transmits to the destination, achieving selection diversity of order N_1. As the best relay transmits, the erroneous relays carry out *OL* and decode their received signals again. With N = 2, N_1=1.

When none of the N–N_1 erroneous relays become error-free after *OL*, the relay availability remains the same, i.e. N_1. Then, the same set of N_1 relay nodes contend for transmission again when retransmission is needed. This means the same relay node is selected for retransmission since the channel rank does not change. The end-to-end PER when the erroneous relay node keeps having errors can be expressed as

$$P_p^{c3.1} = \sum_{i,j=1}^{2} \left\{ \left(P_{p,1}\left(\bar{\gamma}_{SR_j} \right) \cdot P_{p,2}\left(\bar{\gamma}_{OL,R_j} \right) \right) \cdot \left(\left(1 - P_{p,1}\left(\bar{\gamma}_{SR_i} \right) \right) \cdot P_{p,\text{ARQ}_{R_iD}} \right) \right\} \quad i, j = \{1,2\}, \forall i \neq j , \quad (18)$$

where, $P_{p,2}(\bar{\gamma}_{OL,R_j})$ is the error probability of *OL* at the erroneous relay R_j, with the effective SNR being $\gamma_{OL,R_j} = \gamma_{SR_j} + \gamma_{R_iR_j}$.

On the other hand, when N–N_1 erroneous relay nodes become error-free after *OL*, relay availability increases to N_2. If the destination fails to receive initial relay signal correctly, N_2 relay nodes contend for retransmission. Depending on which relay node transmits, i.e. the selected relay, the destination achieves either 2-branch diversity or 3dB improvement in *SNR*. Given R_i transmitted in the 2[nd] slot, the destination achieves $P_{p,2}(\gamma_{R_iD,R_jD})$ conditioned on selection diversity when R_j transmits in the 3[rd] slot or $P_{p,\text{ARQ}_{R_iD}}$ conditioned on selection diversity when R_i retransmits. This can be expressed as

$$P_p^{(2\gamma,2\text{div})} = \sum_{i=1}^{2}\Big\{\int_0^\infty P_{p,\text{ARQ}_{R_iD}} f_{\gamma_{R_iD}}\left(\gamma_{R_iD}\right) F_{\gamma_{R_jD}}\left(\gamma_{R_iD}\right) d\gamma_{R_iD} + \int_0^\infty\int_0^\infty P_{p,2}(\gamma_{R_iD,R_jD}) f_{\gamma_{R_jD}}\left(\gamma_{R_jD}\right) F_{\gamma_{R_iD}}\left(\gamma_{R_jD}\right) d\gamma_{R_iD}\, d\gamma_{R_jD}\Big\}. \quad i,j=\{1,2\}, \forall i\neq j \tag{19}$$

Then, the end-to-end PER when erroneous relay node becomes error-free can be expressed as,

$$P_p^{c3.2} = \sum_{i,j=1}^{2}\Big\{\left(1-P_{p,1}\left(\bar{\gamma}_{SR_i}\right)\right)P_{p,1}\left(\bar{\gamma}_{SR_j}\right) \left(1-P_p\left(\bar{\gamma}_{OL,R_j}\right)\right) P_p^{(2\gamma,2div)}\Big\} \quad i,j=\{1,2\}, \forall i\neq j \tag{20}$$

Finally, the overall average PER of case 3 is the summation of (18) and (20),

$$P_p^{c3} = P_p^{c3.1} + P_p^{c3.2}. \tag{21}$$

Since each case of relay error events are mutually exclusive, the end to end PER of the cooperative ARQ with selection and inter-relay *OL* is the summation of the error probabilities of each case,

$$P_p = P_p^{c1} + P_p^{c2} + P_p^{c3}. \tag{22}$$

In cooperative ARQ that uses distributed relay selection only without *OL*, the number of available relay nodes will be the same in both initial relay transmission and retransmission time. In that case, the end-to-end PERs of case 1 and case 2 are the same as given by (13)-(17). As for case 3, the end-to-end PER is given by (18) without conditional probability $P_{p,2}(\bar{\gamma}_{OL,R_i})$ by *OL* at the erroneous relay node.

IV. Simulation Assumptions And Parameters

The transmit power of each relay node is the same. Each of source-relay and relay-destination channels is independent flat Rayleigh fading channel and invariant within one period of three time slots. In the next three slot period, each channel changes continuously and slowly. To incorporate the effect of path loss in channel fading h_{uv}, the variance of h_{uv} is calculated as $(d_{uv}/d_0)^{-\alpha}$, where d_{uv} is the distance between S-R_i or R_i-D, (u,v)∈{S, R_i, D}, i={1,…,N}and d_0 is the reference distance which is 1. Perfect channel knowledge is available at each receiving node. As for the channel information required for the selection procedure, h_{R_iD} is perfectly estimated at intervals well within the channel coherent time. The relay nodes perfectly decode the ACK/NACK feedback packets from the destination. Table 1 lists the assumed parameters.

Table 1

Path loss exponent (α)	3.5
Number of retransmission	1
Modulations	BPSK, QPSK, 16QAM
Number of symbols/packet	100
Slot length (T_{slot})	10 ms
Maximum time-offset τ_{max}	1 ms
Control factor (λ)	200 μs

Collision occurs owing to the uncertainty interval that consists of propagation delay and transmit/receive switch delay in which two or more relays' τ_i's expire to zero simultaneously [11]. It was shown in [11] collision probability is well below 0.6 % with λ= 200 μs. In simulations, real channel gain instead of a quantized value is used in determining channel quality a_i of each relay. In addition, propagation delay and transmit-receive switch delay are not taken into account. Thus, in the assumed environment, collision does not occur. With the chosen parameters, the possible maximum overhead is only 10 %. In practice, since likelihood of all the relay nodes' h_{R_iD} to fall in deep fade simultaneously is very low, most relay transmission happens at τ_k well within τ_{max}, shortening the contention time.

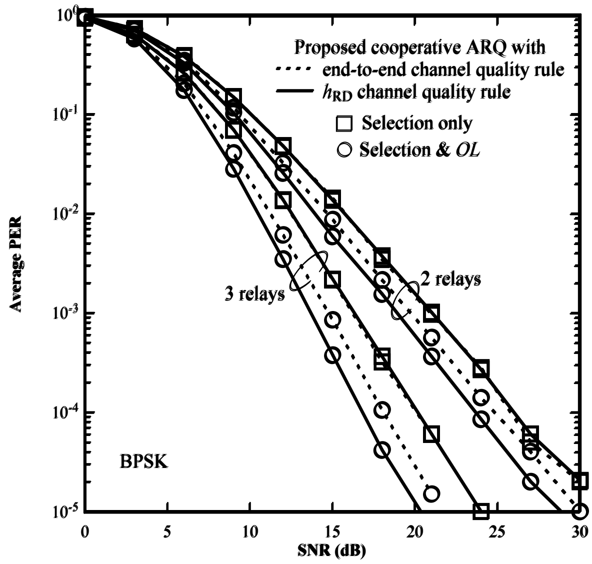

Figure 4 Effect of channel quality decision rule.

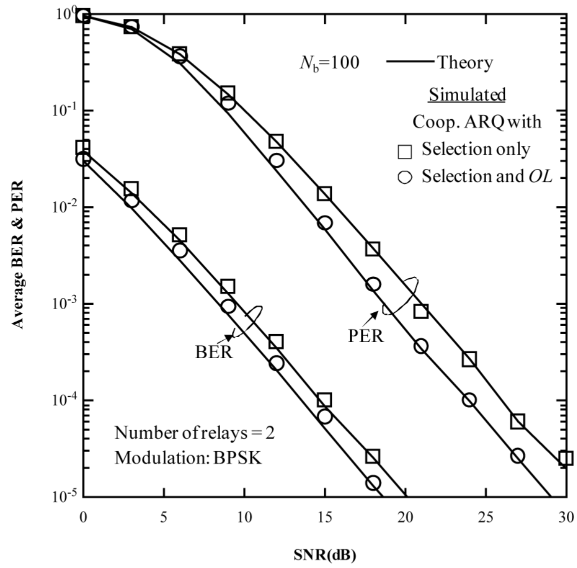

Figure 5 BER and PER comparison: theory and simulated results.

V. Numerical Results

In this section, the end to end performance is evaluated by both theoretical calculation and computer simulation.

The theoretical results are obtained by numerical integration of the expressions derived.

A. Effect of Channel Quality Decision Rules

First, we investigate the effect of channel quality decision rules on the performance of the proposed cooperative ARQ protocol. We compare the performances of distributed relay selection with two different rules: (a) the end-to-end channel based quality decision rule given by (2) and (b) relay-destination channel based quality decision rule given by (3) and (4). For the evaluation in this section, each channel in the system is assumed to have equal average power; thus distances d_{uv}'s are set to one. That means distances between source to each relay node and each relay node to the destination are the same. Fig. 4 plots the performances of cooperative ARQ with selection only and that with selection and *OL* using BPSK in both cases. Each of the both cases employed the two channel quality decision rules (a) and (b). Regardless of channel quality decision rule, it is seen that the cooperative ARQ with selection and *OL* always outperforms cooperative ARQ with selection only. In cooperative ARQ that uses selection only, both channel quality decision rules (a) and (b) provide the same performance. This is because, in the case without *OL*, the relay availability does not change at retransmission. Thus, the relay-destination channel based quality decision rule also has no chance to exploit the increased relay availability. With selection and *OL*, the end-to-end channel based quality decision rule provides poorer performance than its counterpart. Thus, as we discussed in Sec. II, the conventional selection protocol that uses channel quality decision rule (a) is not optimal for the proposed cooperative ARQ where relay availability dependency over source-relay channels decreases in retransmission. The following evaluations use only relay-destination channel quality decision rule.

B. Theoretical and Simulated Results

In this section, the theoretical error rate performance expressions derived in Sec. III are verified by computer simulations. For comparison with the theoretical results, BPSK modulation is assumed and $N = 2$. All the channels involved are flat Rayleigh fading with equal average power. Fig. 5 plots both BER and PER performances. As a reference comparison, the performance of cooperative ARQ with selection only is also plotted. As can be seen, the theoretical results agree with the simulated results, proving the validity of the expressions for error performance of the proposed cooperative ARQ. The result shows that, in equal power Rayleigh fading channels, cooperative ARQ with relay selection and *OL* can achieve performance gain in term of PER about 2 dB over cooperative ARQ with selection only, with $N = 2$ in both cases.

The performance is evaluated also using higher level modulations by simulations. Fig. 6 plots the performances of QPSK and QAM with the number of relays N =2, 3. For all the modulations, it is seen that as the number of relays increases, the performance gain with cooperative ARQ with selection & *OL* increases. This is because improvement in selection diversity order at retransmission increases as N increases. With 16QAM, the improvement is relatively small compared to lower level modulations because more SNR is required to correct errors in amplitude modulated symbols.

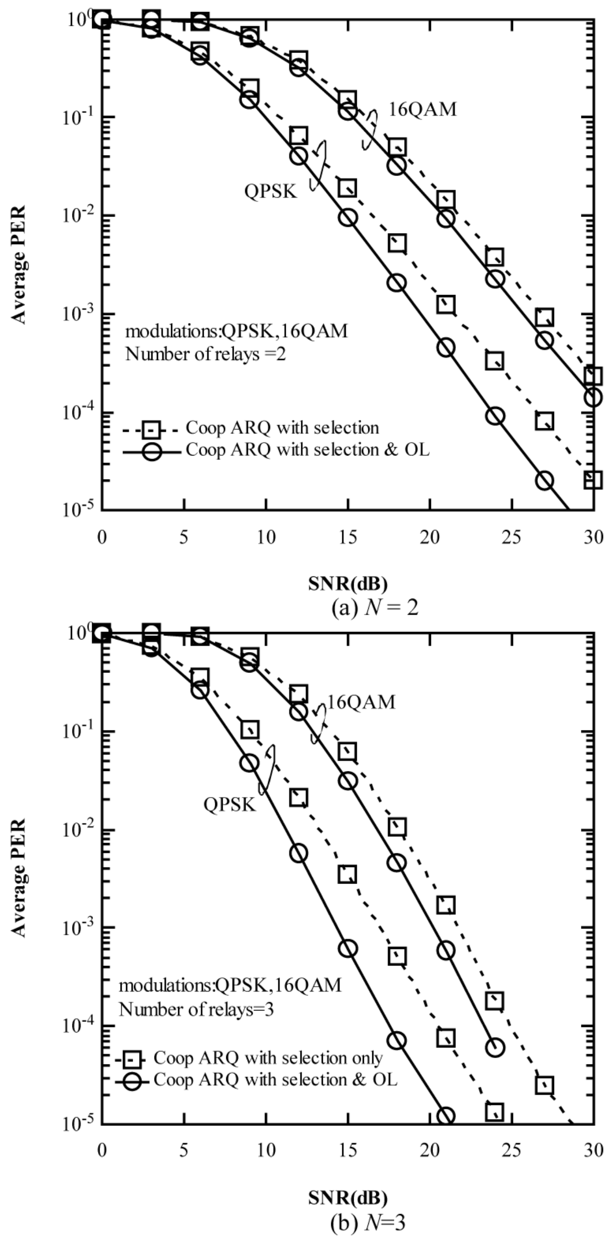

Figure 6 PER with QPSK,QAM in equal power channel

C. Performance with Different Relay Nodes' Locations

Obviously, the performance of proposed cooperative ARQ depends on the inter-relay channel condition. In order to evaluate the performance with various inter-relay channel conditions, positions of two relay nodes, relay 1 and relay 2 denoted as R_1 and R_2, respectively, were randomly distributed using a model shown in Fig. 7. In that model, the source sensor is located at an edge while the destination is at the opposite end. R_1 is on the left side and R_2 is on the right side. Their positions in their respective areas change randomly at each time. As the positions of R_1, R_2 change, the distances $d_{uv} \in (d_{SR_i}, d_{R_iD}, d_{R_1R_2})$ also change resulting in unequal power channels. Consequently, inter-relay channel condition also changes at each time. The effect of shadowing loss is also taken into account and the standard deviation of normally distributed shadowing loss coefficient, η, is 6.5 dB. The distance between the source and the destination d_{SD} is kept as reference distance and remains the same for every set of R_1, R_2 locations. Since the positions of R_1, R_2 vary at each time, the received SNRs at each relay and at the destination also vary. The received SNR with d_{uv}=1 is kept as the reference SNR (SNR_{ref}). From SNR_{ref}, the actual received SNR, SNR_{uv}, at the relays or at the destination can be calculated as,

$$SNR_{uv} = SNR_{ref} \cdot \left(\frac{d_{uv}}{d_{SD}}\right)^{-\alpha} \cdot 10^{\frac{\eta_{uv}}{10}}, u,v \in \{S, R_i, D\}, i = \{1,2\}. \quad (23)$$

In this evaluation, packet arrival rate [18] is used as the performance criterion. Packet arrival rate is defined as the percentage of the information packets from the source correctly received at the destination during a given time interval. Substituting SNR_{uv} in respective PER expressions in (13)-(22), end to end packet error P_p can be calculated. From P_p at each SNR_{ref}, packet arrival rate (PAR) is given by

$$PAR(SNR_{ref}) = 1 - P_p(SNR_{ref}) . \quad (24)$$

Fig. 8 plots cumulative distribution function (CDF) of packet arrival rate with randomly distributed different (R_1, R_2) locations. Moreover performances with different SNR_{ref} = −5, 0, 5dB are also plotted to elucidate the performance variation with SNR_{ref}. The results show that regardless of the inter-relay distances, cooperative ARQ with selection and *OL* always outperforms cooperative ARQ with selection only. For instance, at SNR_{ref}= 0dB, while 80% of the relay position distributions achieve packet arrival rate about 0.66 with selection only, the same percentage of the relay position distributions achieve packet arrival rate about 0.73 with selection and *OL*. When SNR_{ref} is small, the probability that both relays do not successfully receive from the source is high, consequently the probability of conducting *OL* is small. Therefore, performance gain at SNR_{ref} = −5 dB is slightly small compared to SNR_{ref} = 0 dB.

As SNR_{ref} increases, the probability that any one of the relay nodes successfully receives the signal from the source increases. As a result, the probability of conducting *OL* rises. When SNR_{ref} is large enough that the probability of both relays correctly receiving from the source sensor is high, so the probability of conducting *OL* falls. Therefore, the performance difference becomes smaller again at SNR_{ref} = 5 dB.

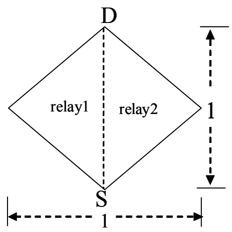

Figure 7 Random relay position distribution model

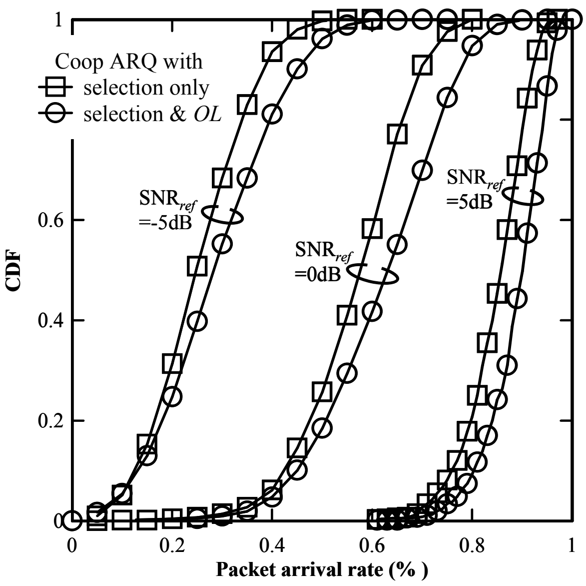

Figure 8 Cummulative packet arrival rate

VI. Conclusion

In this paper, we presented an autonomous cooperative ARQ protocol for a hybrid wireless mobile sensor network. The proposed protocol enables the distributed relays to cooperate in ARQ autonomously. With the proposed cooperative ARQ, achievable selection diversity order is increased in subsequent retransmissions. It was also shown that the proposed selection protocol can make full use of the increased selection candidates. Packet arrival rate improvement of the proposed cooperative ARQ using distributed selection along with *OL* than using conventional distributed selection showed information from the sensor can be sent efficiently and reliably to the destination.

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