rate of 40 000 per second therefore in effect phase is sampled at $(40\,000/M)$ Hz allowing CFO in the range $\pm(20\,000/M)$ Hz to be clearly resolved. In this arrangement a 2×2 (denotes TX × RX antennas) MIMO system can resolve any CFO that is within ±10 kHz. For different MIMO systems this will result in a different number of channel estimation sequences being integrated within each integration period as shown in Fig. 1. The transmit power is constant for all MIMO systems considered therefore the total transmitted energy is the same within each integration period.

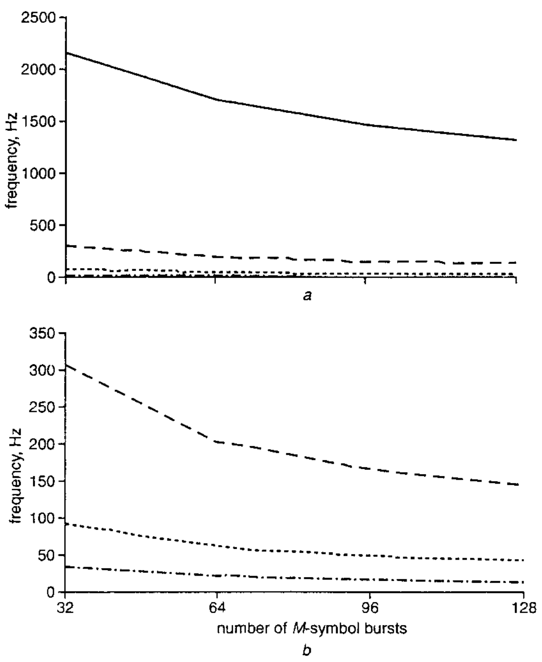

Fig. 2 *Frequency offset mismatch*

a Mean magnitude of frequency offset mismatch in different $M \times M$ MIMO systems, Doppler 10 Hz
b Finer view of mean magnitude of frequency offset mismatch in different $M \times M$ MIMO systems, Doppler 10 Hz
—— 1TX × 1RX - - - 2TX × 2RX
· · · 4TX × 4RX -·-·- 8TX × 8RX

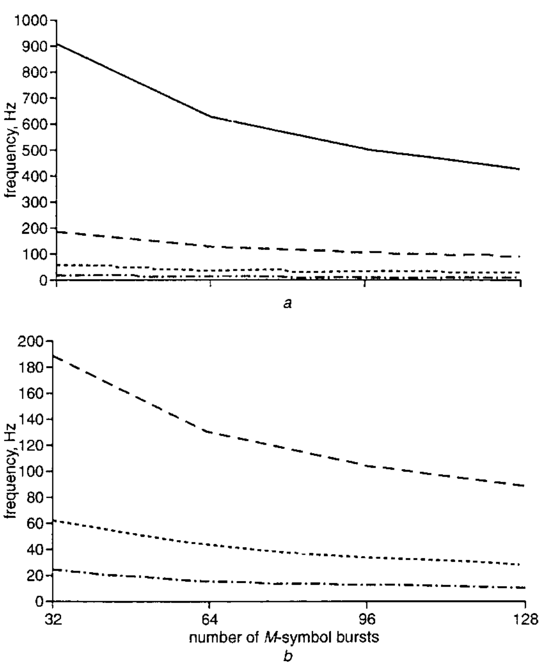

Fig. 3 *Frequency offset mismatch*

a Mean magnitude of frequency offset mismatch in different $M \times 2M$ MIMO systems, Doppler 10 Hz
b Finer view of mean magnitude of frequency offset mismatch in different $M \times 2M$ MIMO systems, Doppler 10 Hz
—— 1TX × 2RX - - - 2TX × 4RX
· · · 4TX × 8RX -·-·- 8TX × 16RX

Results: The actual CFO is set to a nominal worst case of +2 kHz and the performance of the estimator is assessed in terms of the mean mismatch between the actual and estimated CFO. The SNR at each receive antenna is set to 0 dB and Doppler is set to 10 Hz to represent a pedestrian speed of approximately 3 miles per hour at a carrier frequency of 2 GHz. It can be seen from Fig. 2*a* that there is an approximately sixfold reduction in frequency mismatch between the 1×1 and the 2×2 MIMO systems when the integration period is set to 32 bursts. Fig. 2*b* offers a closer view of these results and it is evident that improved transmit and receive diversity of the 4×4 and 8×8 MIMO systems offer significant improvements in estimation performance. The use of increased receiver diversity is now explored for MIMO systems where the number of receive antennas is twice the number of transmit antennas. Results in Fig. 3*a* illustrate that a 1×2 offers over a twofold reduction in offset mismatch using an integration period of 32 bursts compared to the 1×1 system in Fig. 2*a*. Fig. 3*b* offers a closer view of the results shown in Fig. 3*a*.

Conclusion: MIMO channel estimation sequences have been employed to perform CFO estimation. The results indicate that the use of spatial (i.e. both transmit and receive diversity) and temporal signal processing can offer significant improvements in the accuracy of the CFO estimate.

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Energy efficient wireless sensor networks with transmission diversity

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A new transmission scheme which uses two transmitting sensors and space-time block code to provide transmission diversity in distributed wireless sensor networks with neither antenna-array nor transmission synchronisation is proposed. Full diversity and full rate are achieved which enhances power/bandwidth efficiency and reliability. Simulations demonstrate its superior performance in saving transmission energy.

Introduction: Wireless sensor networks contain a large number of densely deployed sensors which form a dynamic multi-hop network. The fact that the sensor battery may not be replenished makes energy efficiency a dominant design criterion. Since sensors may work in uncertain fading environments and wireless transceivers consume a major portion of battery power, it is desirable to improve transmission power efficiency. This is the case, for example, when signals transmitted by sensors near ground experience more rapid attenuation and severe fading [1]. In addition, because low-cost sensors suffer from high failure rate, another serious concern is with the compromise of network efficiency by inadequate reliability of a single sensor. Therefore, efficient and reliable transmission techniques become necessary. However, wireless transmissions have not attracted significant attention, especially those exploiting the unique characteristics of wireless sensor networks for energy efficiency and reliability.

Space-time block codes (STBC) are effective for enhancing transmission power efficiency, and also have affordable complexity and high bandwidth efficiency, which makes them especially desirable for sensor networks. A challenge is that STBC require antenna array and synchronisation among transmitting antennas, neither of which is available in sensor networks with low-cost small-sized sensors. Fortunately, since each transmission by a sensor results in simultaneous reception by multiple other sensors, it is possible for the data packet to be retransmitted simultaneously by multiple sensors. As a matter of fact, there are always multiple standby sensors listening to and receiving signals at the same time [2]. Exploiting this special feature, we propose a multi-transmission scheme where each data packet is transmitted by multiple sensors simultaneously, which effectively builds antenna array, and more important, sensors performing multi-transmission need not be synchronised. In contrast, traditional schemes are single-transmission where only one sensor is selected to perform transmission per hop per routing path [2]. The new scheme utilises two transmitting sensors and the Alamouti code [3] which is the simplest STBC with both full diversity and full rate and has been adopted in 3G WCDMA.

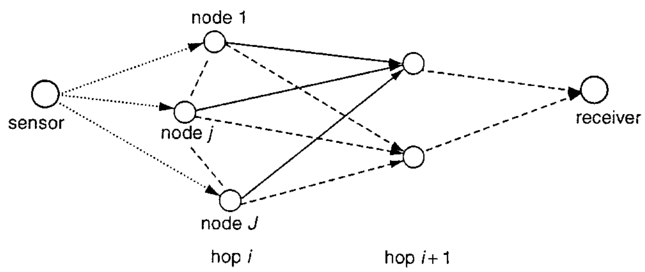

Fig. 1 *Multi-hop wireless sensor network*

Nodes 1 to J receive same data packets from nodes of previous hop, and can transmit them simultaneously to nodes of next hop

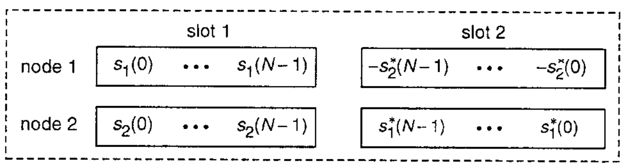

Fig. 2 *Transmission scheme with STBC encoding*

Two data packets transmitted simultaneously by two nodes in every two slots

Transmission scheme: We consider the wireless sensor network illustrated in Fig. 1, where a sensor needs to transmit data packets to the remote receiver through a multi-hop wireless network. In the intermediate hop i, a data packet from the sensor is received by multiple nodes, e.g. nodes $j=1, \ldots, J$. With traditional single-transmission, one of these J nodes is chosen to retransmit the data packet to hop $i+1$. In our scheme, however, two of the J nodes are chosen to perform transmission with STBC encoding.

The transmission scheme is illustrated in Fig. 2. Without loss of generality, assume that nodes 1 and 2 have both received two data packets P_1: $\{s_1(0), \ldots, s_1(N-1)\}$ and P_2: $\{s_2(0), \ldots, s_2(N-1)\}$ from nodes of the previous hop, where $s_i(n)$, $i=1, 2$, are uniformly distributed symbols with zero mean and variance σ_s^2. In slot 1, one of the nodes transmits P_1 to the next hop, whereas the other transmits P_2 simultaneously. Then in slot 2, the first node transmits $\{-s_2^*(N-1), \ldots, -s_2^*(0)\}$, where $(\cdot)^*$ denotes complex conjugate, and the other transmits $\{s_1^*(N-1), \ldots, s_1^*(0)\}$.

Assume channels from nodes 1 and 2 to a receiver in the next hop are Rayleigh flat-fading with coefficients α_1 and α_2, respectively. Channels are quasi-static [3, 4], i.e. keep constant over these two slots and may vary randomly afterwards. Note that sensor failure probability is indirectly included in random fading. Let transmission delays of nodes 1 and 2 be d_1 and d_2, respectively. The receiver obtains T samples per slot. In slot 1, the received baseband signal $x_1(n)$, $0 \le n < T$, is

$$x_1(n) = [\alpha_1 \quad \alpha_2]\begin{bmatrix} s_1(n-d_1) \\ s_2(n-d_2) \end{bmatrix} + v_1(n) \tag{1}$$

where $v_1(n)$ is zero-mean additive white Gaussian noise (AWGN), and $s_1(n)=s_2(n)=0$ if $n<0$ or $n>N-1$. Similarly, the received signal in slot 2 is

$$x_2(n) = [\alpha_1 \quad \alpha_2]\begin{bmatrix} -s_2^*(N-n-1+d_1) \\ s_1^*(N-n-1+d_2) \end{bmatrix} + v_2(n) \tag{2}$$

Construct sample vector $\mathbf{x}(n)=[x_1^*(n) \quad x_2(N-n-1+d_1+d_2)]^H$, where $(\cdot)^H$ denotes conjugate transpose. Then we have

$$\mathbf{x}(n) = \begin{bmatrix} \alpha_1 & \alpha_2 \\ \alpha_2^* & -\alpha_1^* \end{bmatrix}\begin{bmatrix} s_1(n-d_1) \\ s_2(n-d_2) \end{bmatrix} + \begin{bmatrix} v_1(n) \\ v_2^*(N-n-1+d_1+d_2) \end{bmatrix}$$
$$\triangleq \mathbf{H}\mathbf{s}(n) + \mathbf{v}(n) \tag{3}$$

Obviously, (3) is in the standard form of the Alamouti STBC coded signal [3]. The traditional STBC decoding algorithm can be applied, which performs maximum-likelihood detection with linear complexity. Specifically, with the estimated delays d_1, d_2, and channels α_1, α_2, we can estimate symbol vector $\mathbf{s}(n)$ as

$$\hat{\mathbf{s}}(n) = (|\alpha_1|^2 + |\alpha_2|^2)^{-1}\mathbf{H}^H\mathbf{x}(n) \tag{4}$$

This STBC coded transmission scheme achieves full diversity with full rate [3], which means optimal energy and bandwidth efficiency.

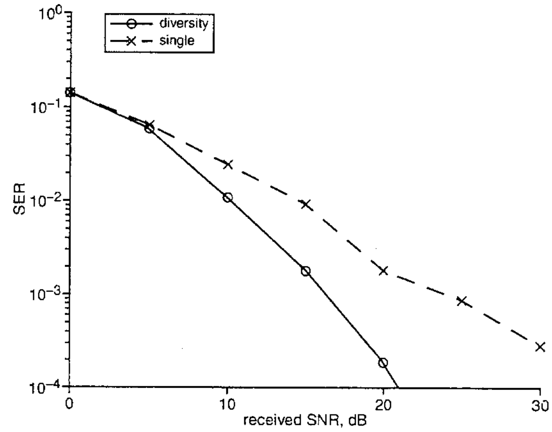

Fig. 3 *Symbol-error-rate against average received SNR*

New transmission scheme (diversity) provides diversity and outperforms traditional single-transmission scheme

Delay and channel estimation: Transmission delays and channels can be estimated efficiently from training, although they may also be obtained blindly, e.g. from received signal energy or differential encoding/decoding [4]. For training, traditional ways with orthogonal codes are not directly applicable because of asynchronous and distributed transmission.

Let the upper bound of transmission delays be D, i.e. $0 \le d_i \le D$, $i=1, 2$. In each packet, let symbols $s_i(n)$, $T_b \le n \le T_e$, $i=1, 2$, be pseudo-noise training sequences, where $T_e - T_b + 1 \ge D$. Then from (3), the sample vectors $\mathbf{x}(n)$, $T_b + \max\{d_1, d_2\} \le n \le T_e + \min\{d_1, d_2\}$, are determined completely by the training symbols. Considering all possible delays $0 \le k_i \le D$, $i=1, 2$, we calculate the corresponding correlation matrices

$$C(k_1, k_2) = \frac{1}{L}\sum_{n=M_1}^{M_2}\begin{bmatrix} x_1(n) \\ x_2(N-n-1+k_1+k_2) \end{bmatrix}\begin{bmatrix} s_1(n-k_1) \\ s_2(n-k_2) \end{bmatrix}^H \tag{5}$$

where $L = T_e - T_b - |k_2 - k_1| + 1$, $M_1 = T_b + \max\{k_1, k_2\}$ and $M_2 = T_e + \min\{k_1, k_2\}$. Then delays can be estimated as

$$\{\hat{d}_1, \hat{d}_2\} = \underset{0 \le k_1, k_2 \le D}{\arg\max} \|C(k_1, k_2)\|^2 \tag{6}$$

where $\|\cdot\|$ denotes Frobenius norm, because with sufficiently long training

$$\lim_{L\to\infty} \|C(k_1, k_2)\|^2 = \begin{cases} 2(|\alpha_1|^2 + |\alpha|^2)\sigma_s^4, & \text{if } k_1 = d_1, k_2 = d_2 \\ 2|\alpha_1|^2\sigma_s^4, & \text{if } k_1 = d_1, k_2 \ne d_2 \\ 2|\alpha_2|^2\sigma_s^4, & \text{if } k_1 \ne d_1, k_2 = d_2 \\ 0 & \text{if } k_1 \ne d_1, k_2 \ne d_2 \end{cases} \tag{7}$$

Note that we need compare only $2D+1$ correlation matrices in (6) because we can first select arbitrary k_2 and then find $\hat{d}_1$ from (6).

After delays are estimated, channel matrix $\mathbf{H}$ can be estimated as

$$\hat{\mathbf{H}} = \frac{C(\hat{d}_1, \hat{d}_2)}{\sigma_s^2} \quad (8)$$

because from (5) we have $\lim_{L\to\infty} C(d_1, d_2) = \sigma_s^2\mathbf{H}$.

The detection algorithm is thus summarised as (i) estimate delays as per (6), (ii) estimate channel matrix as per (8) and (iii) detect symbols as per (4). The proposed transmission and detection scheme is computationally efficient.

Simulation results: We compared our new transmission scheme with the traditional single-transmission scheme, where symbol-error-rate (SER) and energy consumption were used as criteria. Each data packet contained 500 QPSK symbols, of which 50 were training. Channel coefficients were randomly generated over every two slots. Transmission delays were random within $D=5$. We used 1000 Monte-Carlo runs to evaluate each SER with respect to the average received signal-to-noise-ratio (SNR) $E[|x_i(n)-v_i(n)|^2]/E[|v_i(n)|^2]$, $i=1, 2$. Note that with the same SNR, both schemes have the same total transmission power.

Simulation results shown in Fig. 3 indicated that the new transmission scheme had lower SER with the same total transmission power because transmission diversity was exploited to mitigate channel fading, i.e. to achieve SER 1%, the new scheme required 5 dB less SNR, thus saved energy and prolonged sensor lifetime by three times. To achieve SER 0.1%, the transmission power of the new scheme was 8 dB less than that of single-transmission, or the sensor lifetime was six times longer.

Conclusion: In distributed wireless sensor networks with neither antenna array nor synchronous transmission, a new transmission scheme with Alamouti space-time block code is proposed to provide transmission diversity. It is energy efficient and reliable, and is computationally efficient.

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Uplink synchronisation control technique and its environment-dependent performance analysis

Hsiao-Hwa Chen, Yu-Ching Yeh, Cheng-Hsiun Tsai and Wen-Hsiang Chang

The use of uplink synchronisation (ULS) control techniques can turn uplink back to a synchronous operation mode to enhance bilateral data transmission rates of the air-interface. This is especially important for some applications where traffic in both links should be made equally high, such as video conferencing. A modelling method is introduced to study environment-dependent performance of the ULS control in a TDD-based cellular system.

Introduction: The uplink–downlink imparity problem has to be dealt with carefully in designing the B3G systems and motivates us to propose *isotropic air-interface*, which should offer equally good operational characteristics for both uplink and downlink. One way to achieve such a goal is to use the ULS control technique, which has been integrated into the TD-SCDMA standard proposed by China [1, 2]. The technique can also be found useful for the applications in the future 4G wireless, where traffic in uplink channels may not be necessarily lower than that in downlink ones, such as the case of video conference.

This Letter will use the probability of successful ULS control to characterise how well the scheme can work under varying operational environments. The success or failure of the ULS control is based mainly on how well a mobile can estimate the propagation delay from the mobile to its BS. The estimation of propagation delay of the signal transmission from a mobile to a BS is made according to a *random scattering model*, which works on randomly distributed propagation characteristics of a cell. For instance, all variables in this model, such as reflection coefficients, scattering path length, cell size, times of reflection, etc., are considered as random variables. Therefore, the estimated propagation delay, thus also successful probability of ULS control, becomes a function of all those random variables. The obtained numerical results will allow us to evaluate how different cellular environments will affect performance of the ULS control and thus provide us with the necessary information to improve the scheme.

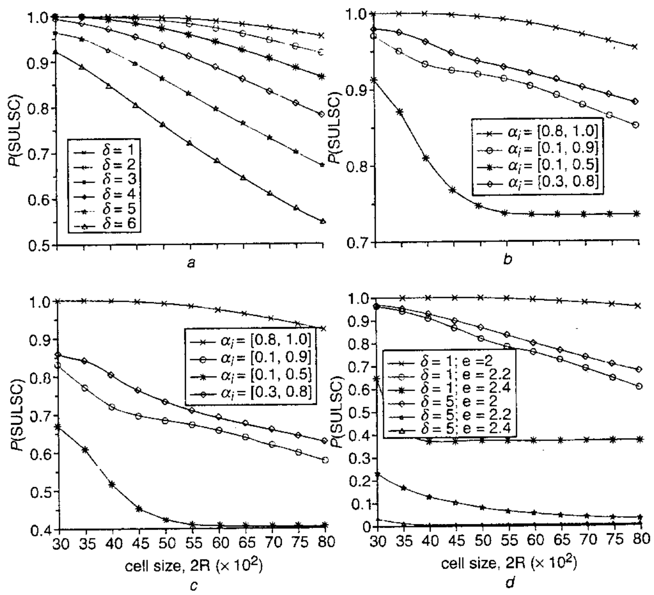

Fig. 1 *P(SULSC) with different environmental parameters*

2R from 3000–8000 m, N Poisson distributed

a α_i uniformly distributed in (0.8,1), $\varepsilon=2$

b $\delta=1$, $\varepsilon=2$

c $\delta=2$, $\varepsilon=2$

d α_i uniformly distributed in (0.8,1)

System model: The analysis followed assumes that a BS of a cell should transmit at a fixed power to different mobiles. A mobile should use line-of-sight (LOS) attenuation rule (with the gradient of two) to roughly estimate propagation delay of the received signal from the BS. In general, the signal from a BS will experience several reflections before arriving at a mobile. Therefore, the estimated propagation distance obtained at a mobile based on the LOS attenuation rule will be inevitably different from the real one.

It is noted that to make a successful ULS control the correct transmission timing for the SYNC_UL burst (in UpPTS slot) [1, 2] at a mobile is the key. If the SYNC_UL burst appears outside the *Search Window* (the length of which is $\Delta = 200$ μs, specified in TD-SCDMA) at a BS receiver, information contained in this SYNC_UL burst will overlap with the time slots of the ongoing transmissions from other mobiles, causing serious interference to them and also making the uplink synchronisation trial itself fail. Thus, we can simplify the derivation of probability of successful uplink synchronisation as the calculation of probability for a mobile to correctly estimate the