Switched antenna diversity within a DECT system

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Abstract

To combat the signal-degrading effects of multipath propagation in a DECT system, diversity techniques can be employed. The performance of a switched antenna diversity scheme based on received power is analyzed and compared with the performance of selection diversity for a frequency non-selective radio channel with either Rayleigh or Ricean fading characteristics. Received output power statistics are chosen as performance measure. Expressions are derived for the performance of two-branch switched diversity with unequal branch statistics, antenna (space) correlation and (partial) time correlation between succeeding time samples. Results show that switched diversity performance is always inferior to selection diversity performance and that the Rice factor influences the diversity gain non-linearly. Both diversity schemes are sensitive to unequal branch statistics, while switched diversity gain deteriorates fastest. Antenna correlation does not have a large influence on the performance of switched diversity. Finally, it is also shown that the diversity gain with switched diversity is reduced considerably if there is only partial time correlation between succeeding time samples.

I. Introduction

The last few years show a rapidly increasing demand for wireless communication systems. The growing trend is to supply different services, such as speech, video or data transmission, with the same network and peripheral equipments. The DECT (Digital European Cordless Telecommunications) standard [1] provides a platform for the wireless digital transmission of speech and data.

DECT will most likely mainly be used for indoor communications, where it has to deal with a very hostile radio environment. Time dependent multipath propagation can cause recurring deep signal fades, severely distorting reception quality. An effective means to combat multipath fading is diversity, which implies that several copies of the transmitted signal are acquired at the receiver and subsequently combined to improve performance.

This paper presents a performance evaluation of such a diversity technique, namely switched antenna diversity, in a DECT system. This evaluation is based on a prestudy performed by Kopmeiners [2]. Performance is compared with that of selection diversity. Only two-branch diversity is considered, i.e. the receiving end acquires only two copies of the transmitted signal. The switching scheme is based on the received power level on both branches [3]. The radio channel is assumed to be frequency non-selective, with either Rayleigh or Ricean fading statistics. Results are given in terms of the cumulative density function (CDF) of the received power after diversity. The influence of several different effects that can degrade switched diversity performance is examined, including unequal branch statistics, correlated signals on both branches and incomplete correlation between succeeding time samples.

II. The DECT radio link

DECT is based on the cellular radio concept with very small cell sizes (micro- or pico-cells, cell radii ranging from 25 m upward) to obtain a very high traffic capacity (typically 10000 Erlang/km^2).

CEPT, the standardization organization of European PTT's, has appointed the 1880-1900 MHz frequency band for DECT applications. Traffic between the base station and the handhelds in each cell is regulated by an FDMA/TDMA/TDD (Frequency Division Multiple Access/Time Division Multiple Access/Time Division Duplex) access protocol. Within the assigned frequency band 10 carrier frequencies are used, evenly spaced by 1.728 MHz. Each of the 10 carriers (FDMA) is subdivided in time into 10 ms frames, each frame consisting of 24 timeslots (TDMA). The first 12 timeslots are used for downlink communication (from base station to handheld), the last 12 for uplink communication (from handheld to base station). The frame structure is shown in Fig. 1.

A pair of timeslots with corresponding sequence numbers in the first and second half of a frame, e.g. 0 and 12, form one duplex channel (TDD). Note that these time slots are separated by half a frame-length, i.e. by approx. 5 ms.

The use of TDMA/TDD makes it possible for DECT base stations to use only one transceiver, instead of one for each carrier (as in an FDMA system). The guard space between time slots allows for a base station to switch between carriers, so adjacent slots can be on different carriers. This leads to a possible 120 duplex channels per base station, of which 12 can be used simultaneously.

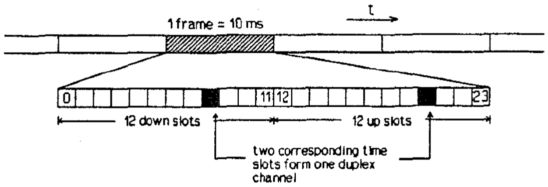


Fig. 1 DECT frame structure

III. Switched and selection diversity principles

With diversity, several versions of the transmitted signal are obtained at the receiver. If these signals are not strongly correlated, the probability that all of them are simultaneously in a fade is much lower than the probability that a single signal is in a fade.

There are numerous ways of obtaining several versions of the transmitted signal at the receiver. Switched and selection diversity are two forms of *antenna* (or *space*) diversity, where multiple spatially separated antennas are used at the receiver, the distance between the antennas being large enough to ensure that signals on different antennas are not correlated.

With *selection diversity* a branch consists of an antenna plus a receiver, see also Fig. 2. On the basis of a certain signal quality measure the 'best' branch at any instant is chosen as output branch, so the signal received on that branch becomes the output signal. Contrary to more complex schemes such as equal-gain combining or maximum-ratio combining, which can achieve a higher output SNR, the SNR of the output signal with selection diversity is only as good as the SNR of the chosen branch. Due to the fact that each branch has its own separate receiver, there is no delay in the selection of the optimum branch. In this paper the instantaneous received signal power is chosen as the selection criterion. The disadvantage of selection diversity is the fact that two radios are needed, which increases the size and cost of the receiver.

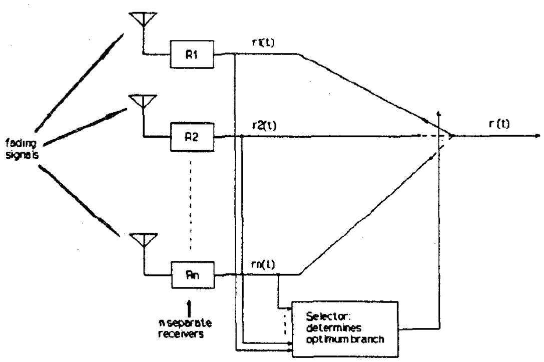


Fig. 2 Selection diversity

With *switched diversity* a branch consists of just an antenna. A switch can connect only one branch at a time to a single receiver, see also Fig. 3. As with selection diversity, instantaneous received signal power on a branch is chosen as the switching criterion; the switching algorithm is as follows: the power on the chosen (first) branch is compared with a certain preset threshold value A. If the power on this branch drops below A, the other (second) branch is chosen. If the power on this second branch is above A, it becomes the output branch. If however, the power on the second branch is also below A, two different follow-up strategies can be discerned:

- a switch back to the first branch is made, which may lead to a period of continuous switching between branches until the power on one of them exceeds A, this strategy is called *switch-and-examine* [4], or
- the second branch stays the chosen branch to avoid needless switching, a strategy called *switch-and-stay*. A switch to the other branch is only made if power on the chosen branch crosses A in negative direction.

All calculations involving switched diversity done in this paper are based on the switch-and-examine strategy.

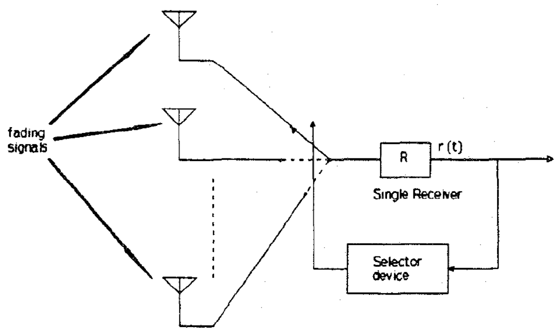


Fig. 3 Switched antenna diversity

IV. Performance analysis

As was mentioned before, only two-branch switched and selection diversity are considered here. Fading has either Rayleigh or Ricean characteristics and is assumed to be frequency non-selective. The instantaneous received power on both branches is represented by the random variables p_1 and p_2. The output power after the diversity operation is denoted by $p_o = c(p_1,p_2)$, where c(.) is the relevant combining function.

IV.A *Independently faded branches with equal statistics*

If the signals on both branches are uncorrelated and have equal statistics, the largest diversity gain is achieved, i.e. we have optimum diversity. To derive the performance expressions, we start with the probability density functions (PDF's) of the faded signal on a single branch. In case of Rayleigh fading, the PDF of instantaneous received power on each branch is given by

$$f_{Ray,p_i}(p_i) = \frac{1}{\sigma_i^2}\exp\left(-\frac{p_i}{\sigma_i^2}\right),\ p_i \geq 0, \qquad (1)$$

where σ_i^2 is the average received power, i = 1 or 2. The PDF for Ricean fading is

$$f_{Ric,p_i}(p_i) = \frac{1}{\sigma_i^2}\exp\left(-\frac{2p_i+s^2}{2\sigma_i^2}\right)I_0\left(\frac{\sqrt{2p_i}\,s}{\sigma_i^2}\right),\ p_i \geq 0, \quad (2)$$

where σ_i^2 is the average scattered component power, $s^2/2$ is the average dominant component power and $I_0(.)$ is the modified Bessel function of the first kind and zero order. An important factor in the case of Ricean fading is the Rice factor K, defined as the ratio of average dominant component power and average scattered component power

$$K \triangleq s^2/2\sigma_i^2. \quad (3)$$

Next, we determine the cumulative density function (CDF) of the instantaneous power of the signal after diversity p_o, denoted by F_{p_o}. It is easily seen that for selection diversity the combining function is the non-linear function $p_o = c(p_1,p_2) = \max(p_1,p_2)$. According to [5,pp.141], $F_{p_o}(p)$ in that case is equal to

$$F_{p_o}(p) = F_{p_1}(p)F_{p_2}(p). \quad (4)$$

For Rayleigh faded branches this is

$$\begin{aligned} F_{Ray,p_o}(p) &= F_{Ray,p_1}(p)F_{Ray,p_2}(p) \\ &= 1-2\exp\left(-\frac{p}{\sigma^2}\right)+\exp\left(-\frac{2p}{\sigma^2}\right),\ p \geq 0. \end{aligned} \quad (5)$$

Substituting $x = (2p_i)^{1/2}/\sigma_i$ in (2), the separate cdf's of p_1 and p_2 for Ricean faded branches are given by

$$\begin{aligned} F_{Ric,p_i}(p) &= 1-\int_{\frac{\sqrt{2p_i}}{\sigma_i}}^{\infty} x\exp\left(-\frac{x^2+(s/\sigma_i)^2}{2}\right)I_0\left(x\frac{s}{\sigma_i}\right)dx \\ &= 1-Q\left(\sqrt{2K},\frac{\sqrt{2p_i}}{\sigma_i}\right), \end{aligned} \quad (6)$$

where Q(.,.) is the Q-function, defined [6,p.28] as

$$\begin{aligned} Q(a,b) &\triangleq \int_b^{\infty} x\exp\left(-\frac{x^2+a^2}{2}\right)I_0(ax)\,dx, \\ &= \exp\left(-\frac{a^2+b^2}{2}\right)\sum_{k=0}^{\infty}\left(\frac{a}{b}\right)^k I_k(ab), \end{aligned} \quad (7)$$

a>b>0, and K is the Rice factor given by (3). The CDF of p_o for Ricean faded branches is found by squaring eqn. (6) and assuming that $\sigma_1 = \sigma_2 = \sigma$ and $K_1 = K_2 = K$.

Since only one receiver is used with switched diversity, the optimum branch cannot be determined instantaneously. Therefore the combining function not only depends on the current value of p_1 and p_2 but also on the values of p_1 and p_2 at the previous sampling instant. If we denote the value of p_i at sampling instant t_k as $p_i(k)$ the combining function for switch-and-examine can be written as [2]

$$p_o = c(p_1,p_2) = \begin{cases} p_1(k) & \begin{cases} 1\ sel. \wedge p_1(k-1) > A \\ \vee \\ 2\ sel. \wedge p_2(k-1) < A \end{cases} \\ p_2(k) & \begin{cases} 2\ sel. \wedge p_2(k-1) > A \\ \vee \\ 1\ sel. \wedge p_1(k-1) < A, \end{cases} \end{cases} \quad (8)$$

where A stands for the switching threshold. The probability that $p_i(k-1)$ is equal to A is infinitely small and therefore does not appear in (8). In terms of probabilities, (8) can be written as

$$\begin{aligned} Pr\{p_o>p\} &= \Big(Pr\{p_1(k)>p \wedge p_1(k-1)>A\} \\ &+ Pr\{p_2(k)>p \wedge p_1(k-1)<A\}\Big)\cdot Pr\{1\ sel.\} \\ &+ \Big(Pr\{p_1(k)>p \wedge p_2(k-1)<A\} \\ &+ Pr\{p_2(k)>p \wedge p_2(k-1)>A\}\Big)\cdot Pr\{2\ sel.\} \end{aligned} \quad (9)$$

Because of the assumption that the average received power in both branches is equal and they have the same statistics, the probability of either branch 1 or 2 being selected is equal, i.e. Pr{1 sel.} = Pr{2 sel.} = 1/2. Given this and the fact that p_1 and p_2 are interchangeable, (9) can be reduced to

$$\begin{aligned} Pr\{p_o>p\} &= Pr\{p_1(k)>p \wedge p_1(k-1)>A\} \\ &+ Pr\{p_2(k)>p \wedge p_1(k-1)<A\}. \end{aligned} \quad (10)$$

If successive time samples have a correlation of 1 so they have equal statistics, the CDF of p_o is

$$\begin{aligned} F_{p_o}(p) &= 1-\int_{-\infty}^{\infty}\int_{\max(p,A)}^{\infty} f_{p_1}(p_1)f_{p_2}(p_2)\,dp_1dp_2 \\ &- \int_p^{\infty}\int_{-\infty}^{A} f_{p_1}(p_1)f_{p_2}(p_2)\,dp_1dp_2. \end{aligned} \quad (11)$$

For independently Rayleigh faded branches, this results in

$$F_{Ray,p_o}(p) = \begin{cases} 1-\exp\left(-\frac{A}{\sigma^2}\right)-\exp\left(-\frac{p}{\sigma^2}\right)+\exp\left(-\frac{p+A}{\sigma^2}\right), & 0 < p < A; \\ 1-2\exp\left(-\frac{p}{\sigma^2}\right)+\exp\left(-\frac{p+A}{\sigma^2}\right), & p > A \end{cases} \quad (12)$$

and for Ricean faded branches

$$F_{Ric,p_o}(p) = \begin{cases} 1 - Q_i(A) - Q_i(p)\left[1 - Q_i(A)\right], \\ \qquad 0 < p < A; \\ 1 - Q_i(p)\left[2 - Q_i(A)\right],\ p > A, \end{cases} \quad (13)$$

where $Q_i(x)$ represents $Q(\sqrt{(2K_i)}, \sqrt{(2x)/\sigma_i})$.

IV.B *Independently faded branches with unequal branch statistics*

If the signals on both branches are independent, but have unequal statistics, diversity gain is reduced. When there is a difference in average power on both branches, the branch with the highest average power will be favoured most of the time, thereby reducing the contribution of the other branch to diversity gain.

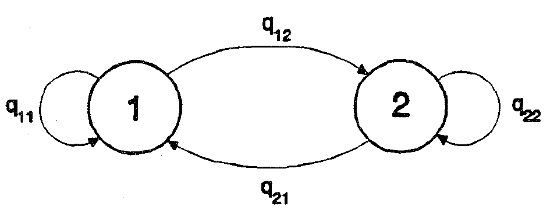
For *selection diversity*, using (4) with unequal average powers σ_i^2, i=1,2, the CDF of p_o for Rayleigh faded branches ($\sigma_1^2 > \sigma_2^2$) is simply

$$F_{Ray,p_o} = 1 - \frac{1}{\sigma_1^2 - \sigma_2^2}\left(\sigma_1^2 \exp\left(-\frac{p}{\sigma_1^2}\right) - \sigma_2^2 \exp\left(-\frac{p}{\sigma_2^2}\right)\right), \quad (14)$$

$p \geq 0$. For Ricean faded branches, using (4) and (6),

$$F_{Ric,p_o}(p) = \left(1 - Q\left(\sqrt{2K_1}, \frac{\sqrt{2p}}{\sigma_1}\right)\right) \cdot \left(1 - Q\left(\sqrt{2K_2}, \frac{\sqrt{2p}}{\sigma_2}\right)\right), p \geq 0. \quad (15)$$

For *switched diversity* we use (9). Since we assume unequal branch statistics, we can no longer take Pr{1 sel.} = Pr{2 sel.}, so (10) is not valid here. To compute the branch selection probabilities, we use the following Markov chain



with state 1: branch one selected and state 2: branch two selected. The state transition probabilities q_{ij} are equal to the probability that power on a branch is either above or below the threshold A, i.e.

$$q_{11} = \int_A^{\infty} f_{Ray,p_1}(p_1)dp_1 = \exp(-A/\sigma_1^2);\ q_{12} = 1 - q_{11}$$
$$q_{22} = \int_A^{\infty} f_{Ray,p_2}(p_2)dp_2 = \exp(-A/\sigma_2^2);\ q_{21} = 1 - q_{22} \quad (16)$$

The steady state solution of this Markov chain gives the branch selection probabilities as

$$Pr\{1\ sel.\} = \frac{1}{1 + (q_{12}/q_{21})} = q$$
$$Pr\{2\ sel.\} = \frac{(q_{12}/q_{21})}{1 + (q_{12}/q_{21})} = 1 - q \quad (17)$$

If we still assume that successive time samples are completely correlated (and branches fade independently!), (9) can be written as

$$Pr\{p_o > p\} = \begin{cases} \left(1 - \exp(-A/\sigma_1^2)\right)\exp(-p/\sigma_2^2)q \\ +\left(1 - \exp(-A/\sigma_2^2)\right)\exp(-p/\sigma_1^2)(1-q),\ p > 0 \\ +\exp(-p/\sigma_1^2)q + \exp(-p/\sigma_2^2)(1-q),\ p > A \\ +\exp(-A/\sigma_1^2)q + \exp(-A/\sigma_2^2)(1-q),\ 0 < p < A, \end{cases} \quad (18)$$

which reduces to (12) if $\sigma_1^2 = \sigma_2^2 = \sigma^2$, so q = 1/2. The state transition probabilities in case of Ricean fading are found as

$$q_{11} = \int_A^{\infty} f_{Ric,p_1}(p_1)dp_1 = Q(\sqrt{2K_1}, \frac{\sqrt{2A}}{\sigma_1});$$
$$q_{22} = \int_A^{\infty} f_{Ric,p_2}(p_2)dp_2 = Q(\sqrt{2K_2}, \frac{\sqrt{2A}}{\sigma_2}); \quad (19)$$

and $q_{12} = 1 - q_{11}$, $q_{21} = 1 - q_{22}$. Inserting (19) in (17) results in the branch selection probabilities Pr{1 sel.} = q and Pr{2 sel.} = 1-q which give the following expression for the probability $p_o(t) > p$ for Ricean faded branches with an unequal K factor

$$Pr\{p_o > p\} = \begin{cases} Q_2(p)\left(1 - Q_1(A)\right)q \\ + Q_1(p)\left(1 - Q_2(A)\right)(1-q),\ p \geq 0, \\ + Q_1(A)q + Q_2(A)(1-q),\ 0 < p < A, \\ + Q_1(p)q + Q_2(p)(1-q),\ p > A, \end{cases} \quad (20)$$

where $Q_i(x)$ is as in (13).

IV.C *Rayleigh faded branches, correlated in space*

Diversity gain decreases if the correlation between the signals on both branches increases. The correlation factor depends on the distance between both receiving antennas, the presence of local scatterers around the receiver as well as on the angle of an incoming signal relative to the imaginary line connecting the antennas [7].

The space correlation factor ρ_s can be defined as

$$\rho_s = \frac{\langle p_1 p_2 \rangle - \langle p_1 \rangle \langle p_2 \rangle}{\sigma_1 \sigma_2}, \quad (21)$$

where <.> denotes statistical averaging. If p_1 and p_2 are independent, $\langle p_1 p_2\rangle = \langle p_1\rangle\langle p_2\rangle$ so $\rho_s = 0$, i.e. p_1 and p_2 are uncorrelated and diversity gain will be highest. For $\rho_s = 1$, i.e. correlated branches, all diversity gain is lost. Branches are assumed to have equal statistics in this section.

We start with the joint PDF of two Rayleigh distributed random variables a_1 and a_2, which is given [8] as

$$f_{Ray,a_1,a_2}(a_1,a_2) = \frac{a_1 a_2}{\sigma^4(1-\rho_s^2)} I_0\left(\frac{|\rho_s| a_1 a_2}{(1-\rho_s^2)\sigma^2}\right) \cdot \exp\left(-\frac{a_1^2+a_2^2}{2(1-\rho_s^2)\sigma^2}\right),\ a_i \geq 0, \tag{22}$$

which reduces to the product of two separate Rayleigh PDF's if $\rho_s = 0$. Transforming (22) with $p_i = a_i^2/2$ (i=0,1) results in the joint PDF for the power of a_1 and a_2

$$f_{Ray,p_1,p_2}(p_1,p_2) = \frac{1}{\sigma^4(1-\rho_s^2)} I_0\left(\frac{2|\rho_s|\sqrt{p_1 p_2}}{(1-\rho_s^2)\sigma^2}\right) \cdot \exp\left(-\frac{p_1+p_2}{(1-\rho_s^2)\sigma^2}\right),\ p_i \geq 0. \tag{23}$$

Given this joint power PDF, we determine the CDF's of power after diversity $p_o(t)$ for the different diversity techniques. Using the fact that p_1 and p_2 in (23) are interchangeable, the CDF for *selection diversity* for correlated branches is given by

$$F_{Ray,p_o}(p) = 1 - \{ \int_p^{\infty}\int_0^{p_1} f_{Ray,p_1,p_2}(p_1,p_2)dp_2 dp_1 + \int_p^{\infty}\int_0^{p_2} f_{Ray,p_1,p_2}(p_1,p_2)dp_1 dp_2 \} \tag{24}$$

$$= \int_0^p\int_0^p f_{Ray,p_1,p_2}(p_1,p_2)dp_2 dp_1.$$

For *switched diversity*, (11) is changed to

$$F_{Ray,p_o}(p) = \begin{cases} \int_0^p\int_0^A f_{Ray,p_1,p_2}(p_1,p_2)dp_1 dp_2,\ 0 < p < A, \\ \int_0^p\int_0^p f_{Ray,p_1,p_2}(p_1,p_2)dp_1 dp_2 + \int_A^p\int_p^{\infty} f_{Ray,p_1,p_2}(p_1,p_2)dp_1 dp_2,\ p > A. \end{cases} \tag{25}$$

No closed expression has been found for equations (24)-(25), they have been solved numerically.

IV.D *Rayleigh faded branches, time correlation in a switched diversity scheme*

If only the base station in a DECT system is equipped with more than one antenna, the handheld can still profit from this antenna diversity if the base station uses the same antenna for downlink transmission as it used for receiving on the uplink, based on the assumption of reciprocity of the channel. In a TDMA/TDD system such as DECT however, there is a time gap of half a framelength between the up- and downlink time slots. During this time the channel characteristics change, and the correlation between these characteristics at the time of the uplink and the downlink slot determines the effectiveness of diversity on the downlink.

Until now, it was assumed that the signal in succeeding time samples has a correlation factor of 1, which results in optimum diversity. In this section we look at the effect of a time correlation less than 1. The value of the stochastic variable p_i at instant t_k is denoted by either $p_i(k)$ or $p_{ik}(t)$.

If we introduce the time correlation factor ρ_t, defined in a similar fashion as ρ_s as

$$\rho_t = \frac{\langle p_i(k)p_i(k-1)\rangle - \langle p_i(k)\rangle^2}{\sigma^2}, \tag{26}$$

we can state that diversity gain is highest if channel characteristics have not changed at all, i.e. $\langle p_i(k)p_i(k-1)\rangle = \langle p_i(k)^2\rangle$ so $\langle p_i(k)p_i(k-1)\rangle - \langle p_i(k)\rangle^2 = \sigma^2$ and $\rho_t = 1$. At the other extreme, if $\rho_t = 0$, succeeding time samples are completely uncorrelated and all diversity gain is lost. The value of ρ_t is determined by two factors: the time between the succeeding samples k-1 and k (time between up- and downlink slots) T, and the fading frequency or Doppler shift, respectively. In [3], the correlation factor for two Rayleigh faded signals is given as

$$\rho_t = J_0(2\pi f_D T) \tag{27}$$

where $f_D = 2\pi f_c v/c$ is the maximum Doppler shift, f_c is the carrier frequency and v the receiver speed. For a DECT system, T is the time between the end of the uplink and the beginning of the downlink slot, which is approximately 5 ms (half the framelength). Some values of ρ_t for different speeds v and T = 5 ms are given in table 1.

Table 1 Values of the correlation factor ρ_t for different receiver speeds v and corresponding Doppler shifts f_D.

v (m/s)	f_D (Hz)	ρ_t
0.5	≈ 20	0.91
1.0	≈ 40	0.65
1.5	≈ 60	0.30
2.0	≈ 80	0.05

This table shows that ρ_t decreases rapidly for an

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