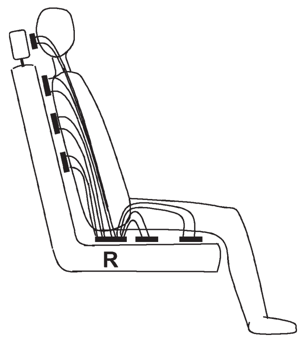

Fig. 5. Pictorial representation of electric field pattern of the proposed method during AO. An adult occupant, when normally seated, makes good capacitive coupling with R and all transmitters.

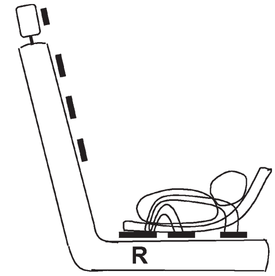

Fig. 6. Electric field line pattern of the sensor system in the presence of an infant in a rear-facing infant seat.

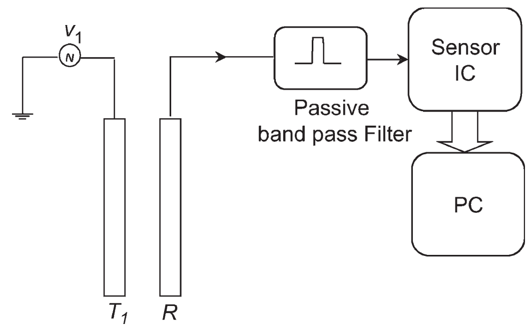

Fig. 7. Block diagram representation of the capacitance measurement system. The receiver signal is bandpass filtered and fed to the sensor IC. Output of the sensor IC is read and displayed by a PC. For brevity, only one transmitter–receiver pair is shown.

the transmitter to the receiver electrode increases in comparison with its value during the shielding mode. This is referred to as the coupling mode of operation, and it is shown using an equivalent circuit in Fig. 4.

When a person sits in a seat equipped with sensor electrodes, as shown in Fig. 1, any one of the aforementioned modes can occur depending on the occupant's position. If the occupant is far from the transmitter–receiver pair, the dominant mode of operation will be shielding and will change to coupling mode once the occupant comes very close to the sensor electrodes. As long as a person normally sits in the seat, the capacitance between the occupant's body and the receiver is stable, and the capacitance between the body and the transmitter gradually increases as the occupant gets closer to the transmitter. Thus, in this condition, the system is in the coupling mode of operation as far as the receiver and transmitting electrodes in the backrest area of the seat are concerned. When a passenger is about to occupy the seat, the electrodes in the sitting area of the seat will be in the shielding mode of operation but will change to coupling mode once the seat is occupied by the passenger. These are the properties exploited in the proposed method to sense human proximity in an automobile seat. A pictorial representation of the pattern of electric field lines between the transmitters and the receiver in the presence of an adult human body are shown in Fig. 5. A transmitter electrode is placed at the backrest head position. The receiver gets a signal from this electrode if the occupant sits normally as shown in Fig. 5. If the person sits in a forward bend (FB) position, the reception from the head position electrode as well as from the other electrodes in the top row of the backrest area will be reduced. Similarly, if the occupant turns left or right, then the corresponding capacitance values will be changed.

In the case of infant seat occupancy, the capacitive coupling with the backrest portion of the seat will be much lower than that for an adult occupancy (AO). Fig. 6 shows the electric field line pattern for such a case. The capacitances between the electrodes in the sitting area and receiver are important for sensing infant seat occupancy as they are in close proximity with the child compared to the electrodes in the backrest area of the seat. In the case of a rearward-facing child, due to the nonuniform volume distribution of the child body (the volume of the leg portions is lower than the volume of the head and shoulder portions), the capacitive coupling with the backrest portion of the seat will be lower than that for a forward-facing child occupancy. Hence, for a rearward-facing child occupancy, the receiver gets lower signal levels from the transmitters placed in the backrest area of the seat compared to a forward-facing child occupancy. This information can be used as an indication for rearward-facing child occupancy. The conductance between the transmitter and receiver can also be measured along with capacitance. This will provide additional information that is useful to distinguish between the human body and other objects such as textbooks, a laptop, food, etc., that may be placed on the seat.

A. *Principle of Capacitance Measurement*

Fig. 7 shows a block diagram representation of the capacitance measurement system with a transmitter–receiver pair. A rectangular excitation is applied to the transmitter. A passive bandpass filter that follows the receiver attenuates unwanted out-of-band frequency components that may be present in the receiver signal [17]. A sensor integrated circuit (IC), based on a carrier-frequency measurement principle [13], [18], measures the capacitance between each transmitter and the common receiver. The capacitance values provided by the sensor IC are read, processed, and displayed in a personal computer (PC).

A functional block diagram of the capacitance measurement system based on the carrier-frequency principle is shown in Fig. 8. As explained in the previous section, the sensor consists of a set of transmitter electrodes and a common receiver electrode. Transmitter electrodes $T_1, T_2, \ldots, T_{11}$ are electrically connected to the buffer units $B_1, B_2, \ldots, B_{11}$ in order. When a measurement cycle is initiated, the control and logic unit (CLU)

TABLE I

RESULTS (NORMALIZED) OBTAINED WITH THE PROTOTYPE SYSTEM. CAPACITANCE VALUES BETWEEN EACH TRANSMITTER AND THE COMMON RECEIVER FOR ES, AO, FB, TR, TL, AND LU CONDITIONS WERE RECORDED. THE VALUE OF CAPACITANCE MEASURED BETWEEN T_4 AND R FOR THE CONDITION AO WAS 24.90 pF

Occupant status	Back rest area of seat						Sitting area of seat				Head
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}
ES	0.132	0.106	0.106	0.125	0.126	0.136	0.145	0.144	0.144	0.157	0.036
AO	0.867	0.517	0.698	1.000	0.687	0.884	0.445	0.909	0.603	0.893	0.171
FB	*0.225*	0.842	0.875	*0.256*	0.996	1.125	0.658	1.564	1.042	1.363	*0.158*
TR	*0.362*	*1.482*	*1.262*	*0.237*	*0.245*	*0.389*	0.782	1.193	1.358	1.583	0.185
TL	*0.224*	*0.222*	*0.298*	*0.297*	*1.170*	*1.450*	0.675	1.645	1.235	1.601	0.173
LU	1.051	0.720	0.820	1.496	0.986	1.122	0.678	*0.115*	0.815	*0.124*	0.190

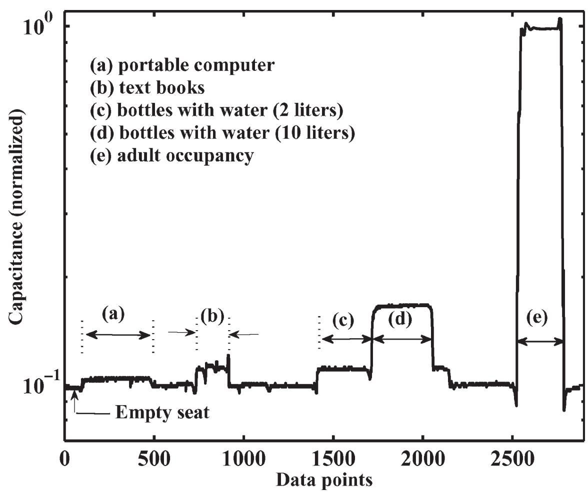

Fig. 11. Capacitance values measured between transmitter segment T_3 and receiver R for various scenarios. A capacitance measurement is also taken and shown for an AO. The results show that the change in capacitance for cases (a), (b), and (c) are very low in comparison with the change in capacitance observed for an AO. In case (d), 20 beer bottles each filled with 500 mL of water were placed in a basket, and the noticed change in capacitance was nearly 5.5 times lower than AO as the volume taken by the basket is a mix of water, glass, and air.

TABLE II

CAPACITANCE (NORMALIZED TO READING FOR AO) MEASURED BETWEEN TRANSMITTER T_3 AND RECEIVER R FROM THE PROTOTYPE FOR DIFFERENT CONDITIONS

Seat scenario	Capacitance
adult occupancy	1.00
adult on a wet blanket (2 mm thick)	1.07
adult with pull over (8 mm thick)	0.82
seat cover (10 mm thick)	0.04
infant seat (70 mm thick)	0.16
infant (10 kg) in an infant seat	0.27

commercially available baby seat with a thickness of 70 mm was placed on the seat. Then, a baby weighting 10 kg was allowed to sit on the baby seat, and an increase of 0.27 per unit was observed in the capacitance readings. These measurement results indicate promising occupancy detection capabilities of the developed sensing system.

Results obtained for different child seat conditions are presented in Table III. Capacitance values were recorded for Vacant Infant seat (VI), Forward-Facing baby (FF), Rearward-Facing baby (RF), Vacant Booster seat (VB), Booster seat with Baby (BB), booster Cushion with Baby (CB), and ten Beer bottles in a vacant booster cushion seat (BE) conditions. A baby-shaped dummy filled with water weighting 10 kg was used for the investigations. In Table III, $T_{(1,4)}$ indicates the average value $(T_1 + T_4)/2$ of the readings obtained from electrodes T_1 and T_4. Similarly, $T_{(2,5)} = (T_2 + T_5)/2$, $T_{(3,6)} = (T_3 + T_6)/2$, $T_{(7,9)} = (T_7 + T_9)/2$ and $T_{(8,10)} = (T_8 + T_{10})/2$. As can be seen from Table III, for the conditions FF and RF, the capacitance values were increased for the electrodes from the backrest area as compared with the condition VI. This is because of the presence of the baby in the sensing volume and, hence, the increase in capacitive coupling between R and the transmitter electrodes in the backrest of the seat. During condition FF, the head and shoulder portions of the baby rest in between the receiver R and the transmitter electrodes in the backrest area. However, during condition RF, the same sensing volume will be occupied by the legs of the baby. Thus, during condition FF, higher capacitance values compared to those of condition RF were noticed for the electrodes in the backrest area. For conditions FF and RF, due to the shielding effect, the measured capacitance values for electrodes in the sitting area were lower than for condition VI. In the sitting area, the receiver and transmitter electrodes are in the same plane and, due to the presence of infant seats, there is more than 5 cm of vertical distance between the baby and the electrode plane. Thus, the child actually acts as a shield for the electrodes in the sitting area. Similarly, for conditions BB and CB, the electrodes in the sitting area are in shielding mode. Thus, for conditions BB and CB, the capacitance values observed for the transmitter electrodes in the sitting area were lower than the corresponding values obtained for condition VB. Also, for conditions BB and CB, due to the dominant coupling effect, the capacitance values read from electrodes in the backrest area were larger than the corresponding values obtained for condition VB. Readings obtained for ten filled beer bottles kept in the booster cushion seat are also given in Table III. As can be seen in Table III, the electrodes in the sitting area are in shielding mode, while those in the backrest area are in coupling mode. However, the shielding and coupling effects observed for this condition are significantly lower than those for conditions BB and CB, which permits one to distinguish between child occupancy and beer bottles placed in a booster seat or cushion.

TABLE III

CAPACITANCE VALUES OBSERVED FOR VI, FF, RF, VB, BB, CB, AND BE ARE PRESENTED

Test case	Back rest area			Sitting area	
	$T_{(1,4)}$	$T_{(2,5)}$	$T_{(3,6)}$	$T_{(7,9)}$	$T_{(8,10)}$
VI	0.118	0.104	0.123	0.175	0.136
FF	0.151	0.146	0.182	0.109	0.079
RF	0.139	0.131	0.164	0.073	0.094
VB	0.117	0.102	0.148	0.159	0.113
BB	0.162	0.148	0.260	0.101	0.080
CB	0.210	0.178	0.348	0.078	0.091
BE	0.153	0.144	0.158	0.124	0.108